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DROUGHT PREDICTION ON THE CANADIAN PRAIRIES

by

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ATMOSPHERIC ENVIRONMENT SERVICE

National Hydrology Research Centre
Saskatoon, Saskatchewan

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DROUGHT PREDICTION ON THE CANADIAN PRAIRIES

A Report to the
Hydrometeorological Research Division
of the Canadian Climate Centre
by

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ABSTRACT

Prior knowledge of the occurrence of drought would permit measures to be taken to reduce many of its impacts on Prairie society. Although the current skill of climate predictions in the one-to-three month time range is not very high, there is reason to believe that significant improvements are possible during the next decade or two. However, considerable research effort will be needed to achieve these improvements.

This report reviews the state-of-the-art of short-term climate prediction and proposes a number of avenues of research, that might be pursued by the Hydrometeorological Research Division, which would lead to a better understanding of the climatic controls on Prairie drought, and ultimately to improved predictions.

RÉSUMÉ

Une connaissance préalable de la probabilité d'une secheresse nous permettrait de planifier afin de beaucoup reduire les répercussions sur les habitants des prairies Canadiennes. Bien qu'au présent la précision des prévisions climatiques pour une période entre un et trois mois ne soit pas élevée, on peut supposer qu'il y aura un progrès important dans les prochaines deux décennies. Cependant beaucoup de recherches seront nécessaires pour atteindre ce progrès.

Dans ce rapport, on fait le compte-rendu des méthodes de prévision climatique et on propose quelques lignes de recherche qui pourraient être poursuivis au Division de la Recherche Hydrométéorologique. Celles-ci meneraient vers une meilleure compréhension des facteurs qui déterminent la secheresse aux prairies et à la fin vers des prévisions ameliorés.

EXECUTIVE SUMMARY

This study was commissioned by the Hydrometeorological Research Division of the Canadian Climate Centre. Its aim is to propose avenues of research for the Division which might lead to the development of methods for the skillful prediction of drought on the Canadian Prairies. The report focuses on the forecasting of meteorological drought for periods of one to three months in the future.

Meteorological drought occurs when an area experiences unusually low precipitation and/or unusually high temperatures (and hence above-average evapo-transpiration) for a prolonged period of time. Variations in precipitation and temperature occur over a wide range of time scales. Short-term variations (up to a few weeks) are controlled mainly by the current state of the climate system and the internal dynamics of the atmosphere. Longer-term variations are influenced more by boundary and external forcing, i.e. by variations in solar energy input, sea-surface temperatures, soil moisture, etc.

Short-term variations can be quite successfully predicted using numerical modelling methods up to a week or so ahead. Longer-term variations are usually predicted using statistical methods, which at present show only marginal skill with regard to temperature, and are even less successful with regard to precipitation. There is, however, good reason to believe that significant improvements can be made. Since the inauguration of the World Climate Programme, following the World Climate Conference of 1979, there has been a tremendous increase in climate research in many countries. This new research is already paying off in terms of increased knowledge of the climate system. The next decade should see a significant improvement in the quality of long-range weather forecasts and for the first time may permit the skillful prediction of drought events up to a season or more in advance.

For the one-to-three month time frame, the most promising avenue lies in determining relationships between precipitation and temperature anomalies and the (more-slowly varying) anomalies in the forcing functions. These relationships can then be used to produce forecasts from observations of the forcing conditions. Eventually, numerical models may be improved to the point where they can realistically simulate these changes in the surface boundary conditions.

Both of these approaches are currently being pursued, and meteorologists are becoming cautiously optimistic about the capability of forecasting climate one to three months ahead, at least in many tropical and sub-tropical areas.

There is a high likelihood that short-term climate prediction for the Canadian Prairies can be improved sufficiently during the next decade or so to permit skillful drought forecasts to be made. To achieve this result, research is needed in the following areas:

1. The spatial and temporal patterns of drought occurrence on the Prairies, particularly the delineation of coherent regions, need to be be established. More information is also required regarding the timing, duration, intensity, spatial extent and predictability of Prairie droughts.

2. There is a need to relate drought patterns to synoptic situations, and in particular to up-stream and down-stream teleconnections. Relationships can then be sought between the synoptic patterns and forcing functions.

3. The associations between these synoptic situations and surface-boundary forcings such as El Niño/Southern Oscillation (ENSO) events need to be investigated.

Possible ENSO effects over the Rocky Mountains merit study since the region is the source of much of the early-summer stream flow in the Prairies.

4. The effects of other local and remote surface anomalies should be investigated, using both studies of historical data sets and numerical simulations. The most promising are likely to be North Pacific Ocean sea-surface temperatures, Arctic sea-ice extent, and North American snow cover and soil moisture.

PREFACE

The Hydrometeorological Research Division of the Canadian Climate Centre undertakes research on hydrometeorological and hydroclimatological problems of both national and regional concern to water managers. In the Prairie Provinces, water managers have consistently identified drought as one of their primary concerns. This view is echoed by the Prairie agricultural community. In particular, these groups are concerned about the monitoring of drought events and the implementation of mitigative actions to offset its effects. They have also expressed an interest in obtaining an advance warning of both the onset and the termination of drought events. This report addresses the possibility of predicting drought and providing this type of guidance.

Drought prediction is a complex problem, and few who have attempted it have met with more than limited success. The Monitoring and Prediction Division of the Canadian Climate Centre has been experimenting with monthly predictions of temperature and precipitation for several years. While the Division has developed considerable skill in forecasting temperatures, it has not yet developed a reliable technique for predicting precipitation. A number of similar initiatives in the U.S.A. and in other countries have had similar experiences with regard to precipitation prediction. On the other hand, recent research results indicate that there may soon be some very reliable forecast techniques, based on teleconnection patterns, for precipitation in tropical regions.

The Hydrometeorological Research Division was interested in having an assessment of current and recent research and technique development related to drought prediction. In particular, we wanted to determine if there are appropriate opportunities for hydrometeorological research related to

drought prediction. Accordingly, a contract was let by the Division to Professor Earle Ripley of the University of Saskatchewan to undertake this study.

Professor Ripley has carried out a very extensive literature review and met with a number of national and international experts studying scientific questions related to drought prediction. As well as reviewing the processes which govern short-term climate variations and drought prediction, Professor Ripley makes a number of recommendations concerning general research needs. In addition, he outlines some avenues of study which could be pursued by the Hydrometeorological Research Division. The extensive literature review and list of references contained in his report make it a valuable starting point for anyone wishing to carry out further work on drought prediction.

It is hoped that the production of Professor Ripley's work as a CCC report will stimulate further discussion on the question of drought prediction. The Hydrometeorological Research Division is very interested in working with agencies which would like to see further work done in this area, and with scientists or research groups who have ideas on ways in which scientific questions related to drought prediction can be addressed. Your views and comments about drought prediction in general, and this report in particular, are invited.

R. G. Lawford, Chief
Hydrometeorological Research Division

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TABLE OF ACRONYMS

AES	Atmospheric Environment Service
ARMA	auto-regressive moving average
CMI	Crop Moisture Index
CWB	Canadian Wheat Board
DERF	dynamical extended-range forecast
ECMWF	European Centre for Medium Range Weather Forecasts
ENSO	El Nino / Southern Oscillation
GCM	general circulation model
NAO	North Atlantic Oscillation
NASA	National Aeronautics and Space Administration
NMC	National Meteorological Center
NO	Northern Oscillation
NOAA	National Oceanographic and Atmospheric Administration
NPO	North Pacific Oscillation
NWP	numerical weather prediction
NWS	National Weather Service
PDI	Palmer Drought Index
PNA	Pacific North America anomaly
QBO	quasi-biennial oscillation
SAO	semi-annual oscillation
SLP	sea-level pressure
SO	Southern Oscillation
SOI	Southern Oscillation Index
SST	sea-surface temperature
STCP	short-term climate prediction (one to three months)
TIO	tropical intra-seasonal oscillation
UKMO	United Kingdom Meteorological Office

Part 1. Introduction

Drought is a recurrent feature of the climate of the Canadian Prairies, and its occurrence often produces severe impacts on many sectors of society. The belief that prior knowledge of its occurrence would permit society to protect itself against these impacts has spurred many searches for predictors over the years. So far, these searches have not been very successful. Marked advances in our understanding of the climate system in recent years, however, give reason to believe that there will be significant improvements in the forecasting of drought within the next decade or two.

1.1 Definition

Every component of the biosphere has a different sensitivity to water shortage. Native plant and animal species, agricultural crops and animals, as well as each sector of society, respond differently. A major factor determining the response is the degree to which each component depends on precipitation, in contrast to surface and ground sources, for its water. Other aspects are the duration of a dry spell and its spatial extent. All of these considerations have led to a variety of definitions of drought (Yevjevich et al., 1983), which may be summarized as follows:

meteorological drought--unusually low precipitation over a large area for a prolonged period.

hydrological drought--unusually low surface-water and ground-water levels over a large area.

agricultural drought--unusually low soil moisture levels over a large area for a prolonged period.

socio-economic drought--an unusual shortage of water that produces an adverse effect on society and the economy.

Since precipitation is the dominant fresh-water input to the biosphere, meteorological drought usually precedes, and is the originating cause of, all other categories of drought. Drought studies may be classified into three time frames (Hounam et al., 1975): past or historical studies; present or drought monitoring; and future or drought prediction. While the first two of these will receive some attention in this report, the main focus will be on the third, the forecasting of

meteorological drought.

1.2 Value of climate information and forecasts to society

"It cannot be stressed too strongly that the value of a forecast to a.... user depends not only on the quality of the forecast and the particular needs of the user, but also on a knowledge by the user of how the forecast should be used.... No forecast is complete without information on the level of confidence of the prediction.... Without the proper background and knowledge, there is a real danger that the user may apply a potentially useful forecast in a harmful way" (Rasmusson, 1987).

The ultimate goal of most world and national climate programs is the minimization of the adverse socio-economic consequences of climatic variability. In fact, the "service" function has always been the primary focus of most national meteorological operations. There are three main prerequisites to the achievement of the above goal: the identification of those human activities most-severely impacted by climatic fluctuations; the determination of which of the affected economies have sufficient flexibility to capitalize on available climate forecasts; and, finally, the development of forecasts with useful skill (Lamb, 1981).

Newark (1982) listed drought as one of the major meteorological hazards affecting Canadian society. Occurring Canada-wide, it was classified as typically affecting an area of a million square kilometres and having a duration of weeks or months. Even in a country as humid as Japan, periodic droughts cause major financial losses, which are only slightly less than those caused by typhoons, heavy rain and cool summers (Uemura et al., 1974). In the United States, droughts have been estimated to produce $1.2 billion in losses annually, which is second only to floods when compared with other natural hazards (Changnon, 1980).

According to the federal government's "Discussion Paper on Drought in Western Canada", the 1977 drought cost western Canada over $100 million in additional electrical power generating costs, $20 million in unexpected fire-fighting charges, $10 million in emergency federal and provincial drought programs, as well as losses in income from tourism and costs of additional water treatment (Department of Regional Economic Expansion, 1978).

There have been many studies of the economic benefits of climate and weather information to society. A survey of U.S. agribusiness, reported by Lamb et al. (1985), found that climate information was being used mostly by integrated pest management consultants, the grain trade, the seed production and food processing industries, and professional farm managers. The main uses were for the design and planning of present and future operations, monitoring of in-season conditions and model-based crop yield prediction.

Phillips (1986) surveyed the economic benefits of climate applications in Canada, and found that climatological information regarding droughts formed the basis for the setting of rates by insurance companies. He also noted that if "the global drought of 1972 (had) been predicted Canada would not have constrained wheat production through the LIFT (Lower Inventories For Tomorrow) program and would have been able to sell the additional production at 1973 prices for a gain of about $1 billion".

The economic benefits of reliable climate predictions to Canadian Prairie agriculture were assessed by McQuillan (1986), who estimated the following annual savings that might be achieved with appropriate management practices based on reliable climate forecasts:

reduction of erosion and salinity losses--$71-83 million;
reduction of losses due to weeds--$21-40 million;
spring cropping choice--$83-85 million;
fall/winter planting decision--$8-16 million;
stubble snow trapping--$49-66 million.

While he recognized that reliable climate forecasts are not yet realizable, McQuillan felt there were several reasons for optimism: satellite data coverage is improving markedly; there is a continuing increase in computing power; and models of the climate system continue to improve.

1.3 Justification for this study

This study was commissioned by the Hydrometeorological Research Division of the Canadian Climate Centre in response to the needs of water resource planners and managers in western Canada. It is intended to be a first step toward designing a research program in the area of drought prediction for the Canadian Prairies.

The occurrence of drought in the region was documented by the earliest explorers. During the 19th century, the Prairies experienced at least 20 major droughts, with the worst occurring in the late 1880s and early 1890s (Stupart, 1917). In the present century, droughts affected at least part of the Prairies in 1910, 1914, 1917-20, 1924, 1929 and 1931, before the major drought of the mid-1930s that resulted in the creation of the Prairie Farm Rehabilitation Administration (Gray, 1978). The newly-formed body was given a mandate to "secure the rehabilitation of the drought and soil-drifting areas in the Provinces of Manitoba, Saskatchewan and Alberta and to develop and promote within those areas systems of farm practice, tree culture and water supply that will afford greater economic security". This has led to the development of programs for monitoring agricultural drought and assessing its effects, as well as to the search for ways of predicting its occurrence and reducing its impacts. More recently, droughts with severe effects on agriculture have occurred during the late 1940s, the late 1950s, the early and late 1960s, and the mid 1970s (AES Drought Study Group, 1986), as well as the mid 1980s.

The mid-1970s' drought (McKay, 1980) prompted the Canadian Government to establish a Federal Task Force on Drought, and to approve a water conservation research program which included a climate forecasting component (AES Drought Study Group, 1986).

Early drought forecasting methodologies focused on the search for natural precursors, such as unusual times of animal migration or hibernation and for periodicities in drought occurrence. Many of the latter type of study have tried to relate drought occurrence to the 11 and 22-year sunspot cycles or to the 18.6 year lunar nodal tide. More recently, other methods have been investigated. Some of these involve the search for historical analogues, others for relationships between the weather at one location on the globe and current or antecedent conditions elsewhere, and still others with the extension of numerical modelling methods far enough into the future to make them useful for climate prediction.

While the present skill of long-range forecasts, particularly of precipitation, is poor, discussions with many experts in the field have led me to believe that there is a high probability of major improvement during the coming years. Since the inauguration of the World Climate Programme,

following the World Climate Conference of 1979, there has been a tremendous increase in climatic research in many countries. This new research is already paying off in terms of increased knowledge of the climate system. The next decade should see a significant improvement in the quality of long-range weather forecasts and for the first time permit skillful prediction of drought events up to a season or more in advance.

1.4 Objective of study

The purpose of this study is to suggest avenues of research, to be pursued by the Hydrometeorological Research Division, which would lead to the skillful prediction of drought on the Canadian Prairies. To this end, the report will focus on the forecasting of meteorological drought for periods of one to three months in the future. Such short-term climate predictions (STCPs) are receiving the attention of the first stream of the World Climate Research Programme (Hoskins and Sardeshmukh, 1987). While the specific prediction of drought may involve the prediction of some index of drought, such as the Palmer Drought Index or the Crop Moisture Index, it will be assumed that meteorological drought can be inferred from STCPs. These may involve the forecasting of upper-level height fields, but are usually expressed in terms of expected anomalies in surface temperature and precipitation. Other information may be combined with such forecasts to provide predictions of hydrologic, agricultural, and socio-economic droughts.

The following chapters will discuss Prairie drought climatology, the global climate system, the current state-of-the-art of drought forecasting, and the preparation and distribution of drought forecasts to users. A final chapter will focus on drought research needs and will present a list of recommendations for research that might be undertaken by the Hydrometeorological Research Division.

Part 2. The Climate System

The forecasting of drought is the anticipation of extreme fluctuations of the climate system that produce unusually dry conditions in a region for an extended period. Drought prediction requires knowledge of the spatial and temporal distribution of these fluctuations and an understanding of the causative factors involved. The global climate system is a complex network of interactions controlling the exchanges of energy and matter between the land surfaces, oceans, atmosphere, and outer space. The energy received from the sun as short-wave radiation drives the system, and ultimately is radiated back to space as long-wave or terrestrial radiation. The balance between energy input and output is closely related to the surface characteristics, such as temperature, albedo, and roughness, most of which vary with time and location. Many of the parameters that control the feedbacks are components of the biosphere.

An important consideration is the wide range of relaxation times of the various components of the climate system. Atmospheric eddies have periodicities ranging from milliseconds (surface boundary-layer turbulence) to a week or more (synoptic-scale cyclones and anticyclones). Oceanic motions exhibit rather longer periodicities, with a peak between 50 and 200 days (Wells, 1986). These range from one to two months in the surface mixed layer to as long as centuries or millenia in the deeper layers (Wright, 1977). Terrestrial surface variations also span a very wide range of time scales, from a few seconds in the case of surface temperature to weeks for normal vegetation growth and years or decades for desertification effects. In the one-to-three month time range, relevant to this study, the dominant forcings will likely be found in the oceanic mixed-layer, and the land-surface components of the system.

The climate feedback diagram, shown as Figure 1 (Robock, 1985a), is adapted from Kellogg and Schneider (1974). The large number of components, and their many interactions, are indications of the extreme complexity of the climate system. Forcings external to the atmosphere (indicated by underlined italics in Figure 1) include solar radiation, geography, latitude and topography, ocean albedo and soil physical properties, solar radiation, volcanic and human activities. Many of these vary too slowly to be of importance in short-term climate prediction--for example, continental

drift and changes in earth-sun geometry. Others, such as volcanic and human activity, lie in the time frame of interest, and their atmospheric effects can be reasonably-well simulated. However, the forcings themselves are still largely unpredictable.

This part of the report will begin by examining the climatology of Prairie droughts from the perspectives of the atmospheric motions that produce them, as well as the resulting surface conditions. This will be followed by an examination of the variations that have been observed in the climate system, on a wide range of time scales. Finally, boundary and other forcings that are likely to be relevant to the STCP of Prairie drought will be analyzed.

2.1 Climatology of Prairie droughts

Our definition of droughts as unusually dry periods prompts us to look for the unusual synoptic situations that produce them (AES Drought Study Group, 1986). In general terms, a reduction in precipitation may be related to variations in one or more of the factors or processes that produce it--i.e. depressions, storm tracks, frontal systems, atmospheric moisture and convective instability. Anomalies in these precipitation-producing elements may occur either randomly, or in response to surface-boundary or external forcing. While the random anomalies will remain largely unpredictable, there is at least the possibility of predicting the effects of local and remote forcings. The first step in this process must be through detailed analysis of the climatology of droughts, examining both the climatic controls (genetic climatology) and the climatic elements (empiric climatology) (Ayoade, 1977).

2.1.1 Genetic climatology

Although the situation has improved during recent years, climatic controls have traditionally received less attention than have climatic elements. This is not due to their lesser importance, but rather because they are far more difficult to measure and quantify. One of the earliest analyses to deal specifically with the Prairies was a study of the climate of the North American grassland by Borchert (1950). His summary of the major circulation features accompanying drought situations in the Great Plains of North America included:

--abnormally-strong westerlies, persisting for one or more months;

--relatively high pressure over the Great Basin and southern plateaus;
--a northward displacement of the usual cyclone path across the central Plains.

A few years later, Currie (1953) attributed precipitation deficiencies on the Canadian Prairies to a lack of moisture-laden air over the region and to lower than average pressure in the Northwest Territories. These findings were confirmed in subsequent studies by Villmow (1956) and Bryson (1966).

Chakravarti (1972) attempted to explain why the peak precipitation in the Canadian Prairies occurs in June and July rather than later in the summer. He related summer precipitation to the storm-track position, which moves from the southern part of the Prairie Provinces in May to the extreme north by July, as the Pacific high extends over the region. He suggested that precipitation anomalies may be related to anomalies in this storm track position, and in the position and intensity of the Pacific high. In a later paper (Chakravarti, 1976), he noted an inverse relationship between areal precipitation in the southern and northern Prairies, which indicated north-south displacement of the normal cyclonic track as the causative factor. While the reasons for these anomalies were admittedly unknown, it was suggested that the ultimate cause of the storm track deviation might be related to North Pacific sea-surface temperatures (SSTs) or sunspot cycles.

Although the cataloguing of synoptic types has been carried out for many parts of the earth, few are applicable to western Canada. Dey (1973, 1982) developed a classification system for drought analysis, having three major weather types, based on 50 kPa ridge and trough positions. He found that droughts were closely related to a blocking-ridge weather type, which forced "migratory cyclones and moist North Pacific air masses to move north of the Canadian Prairies". In 1981, Barry et al. produced a detailed synoptic-type catalogue for western North America, including the Canadian Prairies. Their catalogue identified 31 patterns of 50 kPa heights, into which they were able to fit 93% of the days included in the study (1899-1979). Seven of the 31 were found by Amsden (1985) to be associated with drought periods, who used them in her analysis of the temporal and spatial variables involved in synoptic controls governing dryness regimes in southern Saskatchewan.

The use of a weather-type classification system simplifies comparison and permits the computation of statistical probabilities of various occurrences from the historical records. Precipitation probabilities for the western United States were computed by Augulis (1969), and more recently by Rasch and MacDonald (1975), in relation to major 50 kPa map types for each season. The latter report classified summer flow patterns into ten types, the most frequent of which occurred about half of the time and was associated with a moderate frequency of precipitation occurrence in northeastern Montana. Two of the remaining types were associated with dry conditions in this region, both of which showed strong 50 kPa ridges over Alberta and Saskatchewan.

A recent analysis of dry and wet spells over the Canadian Prairies, and their relationship to 50 kPa circulation was carried out by Knox and Lawford (1988). They found that composited circulations, related to dry and wet spells, were clearly distinguishable, not only over North America but also over the adjacent oceans.

Studies such as the above have provided useful knowledge concerning the synoptic situations that produce drought on the Prairies. There is a need for further studies in this area to improve our understanding of the synoptic controls of Prairie drought and provide a basis for drought forecasting activities.

2.1.2 Empiric climatology

In 1933, Connor responded to requests concerning recent droughts by analyzing Prairie Province precipitation records for possible periodicities. He used a combination of monthly precipitation values, weighted so that they would be closely related to soil moisture. His analysis showed some relationships with sunspots, but since the data used covered only four sunspot cycles, it was impossible to make any general conclusions from the work.

Borchert (1950) investigated the spatial and temporal coherence of North American droughts, as well as correlations between precipitation, cloud cover and temperature. He noted that in major drought years, July precipitation was less than 50% of normal in the Palliser triangle, increasing to 100% further north. Concomitant temperatures ranged from 4 to 2°C above normal in the two regions. A later study of monthly

temperature and precipitation anomalies in the United States Great Plains (Chang and Wallace, 1987) found negative correlation coefficients in excess of 0.5 over much of the southern U.S. Great Plains, decreasing to 0.1 to 0.3 near the Canadian border.

A study of the persistence of extremely wet and dry months in the United States (Gilman and Riedel, 1951) found that pairs of extremely dry (but not extremely wet) months occurred more often than would be expected by chance. There was no evidence of persistence between months from year to year. Namias (1952) found some evidence of month-to-month persistence in temperature and precipitation, except for the periods April to May and October to November which were preferred times for breaks or changes in the persisting conditions. Namias (1978) found temperature persistence between both the autumn and winter seasons and the subsequent spring in the Great Plains region. Van den Dool et al. (1986a) noted that interior U.S. monthly air temperature anomalies exhibited more persistence during the summer than in other seasons, but were generally less persistent than those in coastal regions.

Williams (1962) compared the 1960-61 drought with the 1930s' drought on the Canadian Prairies, and found significant spatial differences between the August-to-July annual precipitation during the two periods. An objective analysis of spatial patterns of growing-season precipitation using principal component analysis was carried out recently by Richman and Lamb (1987). Two examples, using three-day precipitation totals during the May-to-August period, are shown in Figure 2. The two diagrams divide the Prairies into five and six contiguous regions, respectively. The similarity of precipitation patterns within these regions indicates similarity of the synoptic factors producing the precipitation. This suggests that such regionalization may be useful as an areal classification for the analysis, monitoring and forecasting of drought.

In 1960, Laycock used a water budgeting technique to map patterns of soil moisture deficit over the Prairies. On average, mid-summer deficits ranged from over 250 mm in the Palliser triangle to about 50 mm in northeastern Manitoba, while in the driest years the deficits were almost double that. Street and Findlay (1981), Street and McNichol (1983) and Berry and Williams (1985)have also used soil-moisture budgeting techniques to investigate the spatial and temporal

aspects of Prairie droughts. Sargent (1986) compared the climatology of dry periods during 1964-1984 using both observational and general-circulation model (GCM) data. His results indicated that, with some improvement, the GCM could be used to simulate Prairie drought climatology. Both methods found the frequency of occurrence of dry periods to vary inversely as the period length. Further work in this area is still in progress (Street, 1987).

The AES Drought Study Group (1986) looked for correlations between various upper-air parameters and estimated Prairie soil moistures. Using 10-day periods throughout the year, they found moderately high negative correlation between soil moisture and the 85 kPa temperature (i.e. low soil moisture was correlated with high temperature) for lag times of 0 and 10 days. These results indicate that this may be a useful indicator for drought analysis and monitoring purposes.

Using a growing-season drought index (Bhalme and Mooley, 1981) with up to 100 years of data, Oladipo (1986 and 1987) and Oladipo and Hare (1986) investigated the temporal and spatial characteristics of drought occurrence in the interior plains of North America, the vast region extending from Texas to the Canadian Prairies. Since less than three percent of the variation in seasonal drought in any year was explained by the previous year, the authors concluded that the sequential pattern of occurrence was indistinguishable from random. Six spatial patterns of growing-season moisture conditions were found: one with near-normal conditions throughout the interior plains; a second and third showing east-to-west and west-to-east moisture gradients, respectively, across the Plains; and a fourth showing a general south-to-north moisture gradient. The length and severity of drought occurrences varied from sub-region to sub-region, and large-scale droughts that affected the whole region were rare. This view of Prairie droughts as being of limited spatial extent conflicts with the statement of Newark (1982) mentioned earlier in this report, but is consistent with the findings of other studies, such as those of Williams (1962). The findings of Oladipo showed a strong tendency for wetter conditions in the northern parts of the Canadian Prairies when the southern North American Plains experienced drought. Droughts affecting the southern and central Great Plains tended to be more spatially-coherent than those elsewhere. Drought-frequency power spectra were dominated by periodicities near two (QBO), three (ENSO?) and five years. However, only the 2-year oscillation appeared to

have spatial coherence. The other peaks varied between even nearby stations. No lunar nodal cycle signal could be found, and even the 11-year sunspot cycle appeared at only a few stations.

2.2 Variations

Spectral analysis of meteorological data sets reveal a number of quasi-periodic variations covering a wide range of time scales (Lumley and Panofsky, 1964; Kutzbach, 1974; Gilman, 1982; Folland, 1983). Those having periods longer than a few weeks may be termed climate-scale variations, and may be divided into recognizable fluctuations or **climatic signals** and unrecognizable random fluctuations or **climatic noise**. The relative strengths of the climatic signals vary with height in the atmosphere, with geographical location, and with time of year.

The variations have been composited into a spectrum of climate-system variability by Mitchell (1976), from which the diagram presented in Figure 3 has been adapted. The y-axis represents a composite of all climatic parameters, with a strong emphasis on temperature. The sharp peaks indicate strictly periodic variations, while the broader maxima represent quasi-periodic or aperiodic components. The right half of the diagram shows weather variations, with time scales from about an hour to a month (Holton, 1982). The left half shows climate variations with periods from a month to a century. Longer-period variations, which were included on Mitchell's original diagram, are beyond the scope of the present study. The logarithmic time scale is useful for displaying the wide range of periods involved, but has the disadvantage of making the variance values somewhat harder to interpret. A unit area near the left side of Figure 3 represents a much greater contribution to the total variance than a unit area near the right side of the diagram. The high-frequency end of the spectrum of climate variations is dominated by sharp peaks for the annual cycle and its first two harmonics (at 6 and 4 months, respectively). To the left of the annual spike is a broad peak representing interannual variations such as the quasi-biennial oscillation and the Southern Oscillation. Beyond that are further peaks which may be related to lunar and solar forcing.

For discussion purposes, the climate variations being considered in this study will be divided into intra-annual,

inter-annual and inter-decadal time scales. A number of oscillations of variable duration, such as the northern oscillation and the zonally-symmetric see-saw, will be discussed under inter-annual climate variations, although they might equally well fit in the intra-annual category.

2.2.1 Intra-annual climate variations

Even under constant forcing conditions, the climate system will undergo variations due to its own internal dynamics. These types of variations dominate the right-hand side of Figure 3, while the left-hand side of the diagram shows variations that are boundary and externally forced. From the point of view of climatic predictability, the right half of Figure 3 is a region of **climatic noise** (Madden, 1981; Gilman, 1982). As we move towards the left from the 0.01 year line, we encounter a pulse with a period of about two weeks which is believed to arise from internal instabilities in the atmosphere's dynamics (Gilman, 1982). An example of this are the disruptions to the zonal flow of the westerly belt produced by **blocking** situations. Kidson (1986) reported 20-30 day cycles in the zonal wind index in both hemispheres, and postulated effects on mid-latitude temperature gradients and the occurrence of blocking events.

At a period of 0.1 year (about 1 month) on Figure 3, we enter the **climatic-signal** region, in which surface boundary and external forcing are believed to control the variations. Precipitation cycles with periods in the range of 15-30 days have been noted by Brier and Bradley (1964) and Rosenberg and Coleman (1974). Lunar tidal effects have been proposed as an explanation (Gribbin, 1978).

Madden and Julian (1971) were the first to notice a 40-50 day pulsation in tropical pressure, zonal winds and cloudiness that develops over the Indian Ocean and moves eastward, dying out over South America (Kerr, 1984). Lau and Chan (1986) have postulated that this cycle represents an intrinsic mode of oscillation of the tropical atmosphere and may serve, through episodic amplification, as a trigger of El Niño/Southern Oscillation (ENSO) events. While the phenomenon itself is limited to the tropics, it may affect the mid-latitudes through an interaction with the ENSO. A theory for this tropical intra-seasonal oscillation, or TIO (Chao, 1987), has been proposed by Lau and Peng (1987) and tested by numerical modelling.

Semi-Annual Oscillation

Semi-annual oscillations (SAOs) in the zonal wind and zonal mean temperature have been found in the middle atmosphere of the tropics, as well as at higher latitudes (Gao et al., 1987). They appear to be related to a global-scale meridional circulation. In the northern hemisphere, the strongest SAO in temperature occurs in the polar upper stratosphere during the winter. Analysis suggests polar stratospheric warming as a causative factor.

2.2.2 Inter-annual climate variations

These longer-lived variations are dominated by the quasi-biennial oscillation and ENSO, and may play important roles in the prediction of Prairie droughts. Inter-annual variations may be related to shorter-period variations and/or boundary forcings.

Quasi-biennial oscillation

The small peak at 2.1 years in Figure 3 represents the strongest signal, of period greater than one year, in the global climate system. This is the quasi-biennial oscillation (QBO), an east-west flip-flop in zonal stratospheric wind in the tropics every two or three years. A description of the QBO and a summary of possible explanations have been given by Wright (1971), and Naujokat (1986) has provided a recent analysis of QBO data. Bhalme et al. (1987) found that Indian monsoon rainfall tended to be below normal during the east phase, and above normal during the west phase, of the QBO. Evidence of this pulse has also been found in the mid-latitudes (Landsberg et al., 1963; Folland, 1977; Parker, 1982). Analyses by Holton and Lindzen (1972) and Naujokat (1986) have shown that the maximum amplitude of the QBO is near the 2 kPa level; the easterly-phase winds are usually stronger than the westerly winds; and the wind regimes propagate downward as time progresses. A recently-discovered connection between the QBO and solar-cycle effects on climate will be discussed later in this section.

El Niño/Southern Oscillation

A number of other interannual oscillations have been known for many years (Rasmusson, 1984). Walker and Bliss (1932) described oscillations in the North Atlantic and the North

Pacific as well as the larger and more pervasive Southern Oscillation (SO). The latter manifests itself as an aperiodic "flip-flop" in atmospheric mass between the eastern and western regions of the tropical Pacific Ocean (Fig. 4). It is tightly linked to the annual cycle, with its onset tending to coincide with mid winter in the Northern Hemisphere. Though the average period is just over three years it varies widely from two to ten years (Rasmusson and Carpenter, 1982). There was a resurgence of interest in the SO in the mid-1960s (Troup, 1965), which led to the discovery of a connection between the SO and El Niño (Berlage, 1966; Bjerknes, 1969).

The earliest reports of El Niño date from the time of the first Spanish explorers on the west coast of South America, who named the periodic increase in temperature of waters off the coast of Peru after the Christ child because of its frequent occurrence about Christmas time. While the warming occurs quite frequently, in certain years it is excessive and persists for several months. It is these occurrences that are linked to the Southern Oscillation.

The Walker circulation (Barnett, 1977) is caused by the usual east-to-west SST gradient in the equatorial Pacific. Air rises over the warmer waters of the western Pacific, and subsides over the cooler eastern Pacific waters, producing an easterly flow at the surface between the two. These easterly winds reinforce the SST pattern by producing upwelling of cold deep ocean water near the South American coast, and piling up warm surface waters in the western Pacific. ENSO represents a departure of this pattern from normal (Philander, 1982; Glantz et al., 1987). A typical chronology of the SST anomalies associated with ENSO is presented in Figure 5. Prior to the initiation of ENSO, the trade winds are stronger than usual, producing a positive SST anomaly in the western Pacific and a negative anomaly near the South America coast. Sea-level pressure (SLP) anomalies are positive in the eastern Pacific and negative in the west, resulting in positive values of the Southern Oscillation Index (the difference between normalized SLPs at Tahiti and Darwin). About December, the trades weaken and SSTs begin to rise in the central Pacific. By April (Fig. 5a) elevated SSTs appear off the South American coast, and the SOI reverses sign. The trend continues until the mature stage is reached during the northern hemisphere winter (Fig. 5c). By this time, there is a huge area of anomalous westerly winds and warm SSTs over much of the tropical Pacific, and SLP is much higher than average at Darwin, and much lower than

average at Tahiti. The anomaly starts to recede during the northern hemisphere spring so that conditions return to normal by late summer or autumn.

A situation opposite to El Niño also occurs. Characterized by below normal SSTs and strong southeasterly trade winds, this anomaly has been termed "anti-El Niño" by Quinn et al. (1978) and Robock (1985b), and "La Niña" by Philander (1985). Other authors (e.g. Van Loon and Shea, 1985) have used the terms "Warm Event" for El Niño and "Cold Event" for the anti-El Niño.

ENSO events have been related to a number of associated effects in the tropics, including changes in pressure and precipitation patterns, and tropospheric temperatures. Similar effects have also been found at higher latitudes. An example, relevant to the Canadian Prairies is the tendency for the Pacific/North American pattern (Wallace and Gutzler, 1981) to occur during a warm ENSO event. Ropelewski and Halpert (1986) found a consistent positive temperature response over the Canadian Prairies to warm events, particularly during the winter following the ENSO peak. The precipitation response, however, was less obvious with only a small effect during the same winter. Emery and Hamilton (1985) found that the northeast Pacific atmospheric circulation tended to be more vigorous during the mature phase of warm ENSO events, and weak during cold ENSO events. However, they found numerous exceptions to this general tendency. In fact, each ENSO event has its own distinct characteristics, and produces different teleconnected responses (Yarnal, 1985). The major tropical and extra-tropical effects of ENSO are summarized in Figure 6.

Studies of the time evolution of ENSO events have revealed many precursors. Using lag correlation analysis (Wright, 1977) found a number of regions where related surface or upper-air anomalies tend to precede, or follow, changes in the SOI . For example, anomalies have been noted in the atmospheric flow and SSTs during the year preceding a warm event (Van Loon and Shea, 1985). These include a weaker than normal surface trough over the South Pacific Ocean between April and September, which becomes stronger than normal the year of the event. SSTs to the east of Australia are higher than usual the year before, decreasing in the year of the event. Reversal of these precursors is an indication of the arrival of a cold event (La Niña). Newell et al. (1982) found the earliest ENSO precursors to be anomalies in SST near Wake Island and in wind velocity

near Easter Island, that appear up to a year in advance of the SOI response. Wright (1986a) described three largely independent SO precursors: one in the southeast Pacific, characterized by anomalously high SST, low atmospheric pressure, low cloudiness and weak winds, which tends to occur in the December to February prior to a year of low SOI; a second in the equatorial Atlantic, characterized by anomalously high SST which tends to follow a year of low SOI and precede a year of high index; and a third near northern Australia, having low SSTs in every season, associated with a trend towards higher SST in the equatorial east Pacific. Nicholls (1985) found a close relationship between drought severity in Australia as a whole and ENSO indices, with a link to tropical Australian air temperatures during the preceding summer.

There have been attempts to simulate actual ENSO events, as distinct from their effects, using numerical models (Hurlburt et al., 1976; Barnett, 1977; Lau, 1981; Inoue and O'Brien, 1984 and 1986). Some success has been achieved recently using simple (Cane and Zebiak, 1985; Cane et al., 1986), as well as more complex, coupled atmosphere-ocean models (Meehl, 1987).

Northern Oscillation

A Northern Oscillation, also noticed by Walker (1923), has received considerably less attention than its southern counterpart. The NO manifests itself as a periodic reversal in SLP anomalies between mid-latitude Eurasia and the Mediterranean area (Fig. 7), particularly between January and April (Raman and Maliekal, 1985). Thus far, little is known about the cause and recurrence interval of this fluctuation, although some correlation with the Indian summer monsoon has been noted (Raman and Maliekal, 1985).

North Atlantic Oscillation

The North Atlantic Oscillation is a winter-time pressure alternation between the Azores high and the Icelandic low (Fig. 7), reported by Walker and Bliss (1932). It has been well documented by Van Loon and Rogers (1978) who studied its seesaw effects on winter temperatures in Greenland and northern Europe. In searching for a causative factor, they noted that the NAO was intimately associated with changes in the frequency of atmospheric circulation types, and was unlikely to be caused by variations in insolation or

atmospheric composition. They also found relationships between the NAO and pressure anomalies over the North Pacific, the Rockies, and elsewhere in the northern hemisphere. Rogers (1984) investigated effects of both the SO and the NAO in the northern hemisphere, and found that although the two appeared to be uncorrelated, one could enhance the other when they occurred simultaneously. He noted that the NAO had a mean recurrence interval of 7.3 years. Recently, there has been increasing interest in the effects of the NAO on rainfall in northeastern Brazil (Palmer, 1986a) and in Morocco (Lamb and Peppler, 1987).

North Pacific Oscillation

A weak Pacific analogue of the NAO was also found by Walker and Bliss (1932). The NPO pressure flip-flop is between the Bering Sea area and the tropical and subtropical Pacific (Fig. 7). Rogers (1981) analyzed the NPO for the winters between 1906 and 1978, and found it was associated with variations in the strength of the westerlies over the Pacific and North America, resulting from longitudinal variations in the position of the Aleutian low. He found that the NPO modes were associated with variations in North America temperature and precipitation, and with SSTs and ice cover in the North Pacific. The winter temperature flip-flop between Alaska and Edmonton showed a negative correlation coefficient of 0.46. Months of January having negative Bering Sea pressure anomalies were up to 12°C warmer and 10-20 mm moister than their positive-anomaly counterparts over the Canadian Prairies. Although it has a similar recurrence interval to the NAO, the NPO is aperiodic, and does not appear to be associated with hemispheric mean temperature trends. The NAO and NPO are considered to be separate patterns of teleconnections of SLP and zonal winds over the northern hemisphere (Rogers, 1981).

Pacific/North American Oscillation

Dole and Gordon (1983) identified three regions of persistent pressure anomalies at mid to high latitudes during the northern hemisphere winter. These were the North Pacific to the south of the Aleutians, the North Atlantic to the southeast of Greenland, and northern Siberia. The first of these has been termed the Pacific/North American (PNA) anomaly by Wallace and Gutzler (1981). It is a situation in which there is a strong negative pressure anomaly to the south of

the Aleutians, a positive anomaly over the northwestern U.S. and southwestern Canada, and a weaker negative anomaly over the southeastern U.S. The reverse anomaly also occurs, but is less stable than the one described. Horel and Wallace (1981) found evidence for the boundary-forcing (from Pacific SSTs) of the PNA pattern, while GCM experiments by Lau (1981) indicated that it may also occur without external forcing (Dole, 1986).

Zonally-symmetric see-saw

The observed negative correlation between zonally-averaged SLP anomalies at low and high latitudes is too large to be explained by the NAO and NPO alone (Wallace and Gutzler, 1981). Possible other factors that may be involved are the QBO as well as sudden stratospheric warmings. Ebdon (1975) noted that, in wintertime, the east phase of the QBO was associated with higher sea-level pressures in the Arctic and lower SLPs in temperate latitudes than the west phase.

In summary, all of these low/high latitude pressure flip-flops may have significant effects on temperature and precipitation patterns in the Prairies, and are likely to be important factors in any drought forecasting scheme.

2.2.3 Inter-decadal variations

Variations on this time scale are likely to be due to external forcings, related mainly to solar energy variations. The dominant forcing functions appear to be the 11 and 22-year sunspot cycles and the 18.6-year lunar nodal tide.

While the assessment of Pittock (1978) that, "little convincing evidence has yet been produced for real correlation between sunspot cycles and weather or climate", is probably still valid, it is possible that a link may soon be (or may already have been) discovered. Recent detailed analysis of long-term temperature and precipitation data at Toronto (Godson, 1988) revealed only a weak correlation with solar activity, that showed some variation with time (on a decadal scale) and with season.

Although many have searched for a mechanism by which the sun and moon might affect weather and climate (Siscoe, 1978; Goldberg, 1979; Gough, 1986), a satisfactory explanation of how this might occur remains to be found. Recent Work by Labitzke and van Loon (1987) showed that when the QBO was in

its west phase, stratospheric temperatures and geopotential heights were positively correlated with the solar cycle at high-latitudes, and negatively correlated at mid- and low-latitudes, while the converse held true when the QBO was in its east phase. Significant correlations were found in tropospheric geopotential heights and sea-level pressure as well, especially during the west phase over North America and adjacent oceans. There is preliminary evidence of effects on North American temperature and precipitation patterns as well (Van Loon, 1987). Further work must be carried out to find an explanation for this apparent link between the QBO and solar activity.

2.3 Boundary forcings and teleconnections

Surface boundary conditions exert an influence on the climate system mainly through variations in their optical and thermal properties and changes in their spatial extent. On the basis of surface cover, the earth may be broadly classified into areas of water, snow, ice and land (Fig. 8). The march of the seasons produces an annual periodicity in the areas of snow and ice cover, and in the distribution of vegetative cover and soil moisture, for example. Superimposed on these regular cycles are large fluctuations, spanning a wide range of time scales, caused by synoptic-scale weather variations. The major examples of local and remote (teleconnection) responses of the climate system to boundary forcing will be discussed in the following sections.

2.3.1 Sea-surface temperature

The important effects of atmosphere-ocean interactions on short-period climate fluctuations have been underlined by Barnett (1979) and Namias and Cayan (1981). The atmosphere acts on the oceans mainly through the mechanism of wind stress, while the oceans affect the atmosphere principally through their surface temperatures. Sea-surface temperature variations are largely produced by changes in atmospheric winds and solar radiation, although deeper-oceanic factors (mainly thermohaline gradients) may also be involved. The long relaxation time of the oceans means that SST anomalies, once produced, tend to persist for months or even years (Barnett, 1979). Thus, any global climate response to these anomalies can be expected to exhibit comparable temporal persistence, although this will usually be masked by weather-scale noise. Many SST anomaly patterns have been noted to recur on a

regular basis. An analysis of North Pacific Ocean SSTs, using empirical orthogonal functions was presented by Barnett and Davis (1975). They found that the major SST variability occurs just east of Japan where the warm Kuroshio and cold Oyashio currents collide. These variations were noted by Su and Pu (1986) to be correlated with El Niño, and are likely to have an influence on the climate of the North Pacific Ocean and western North America.

There have been many studies of both the local and remote responses of the climate system to SST anomalies. Most of these relate to El Niño, which was discussed in a previous section. More general relationships have been studied by Webster (1981), and the effects of SST anomalies on atmospheric blocking were analyzed by Shukla (1986). Atmospheric circulations at high-latitudes have been related to seasonal trade winds and low-latitude SSTs by Harnack et al. (1982), who found significant correlations at lags of one, two and four seasons. Connections have been found by Folland et al. (1986) and Palmer (1986b) between rainfall in the Sahel and world-wide SST anomalies. Lough (1986) analyzed relationships between tropical Atlantic SSTs and rainfall in Subsaharan Africa, while numerous investigators (Ratcliffe and Murray, 1970; Ped, 1980; Palmer and Sun, 1985; Cayan, 1986 and Moene, 1986) have found some effects of North Atlantic SSTs on European pressure and precipitation patterns, Russian droughts and the general atmospheric circulation.

2.3.2 Snow and ice

The climatic role of snow cover has been summarized by Kukla (1981). He called it "the critical variable of the climate system because of its high reflectivity, high emissivity, low water vapour pressure, and low conductivity". In a few hours, a snow cover may be deposited over a substantial area of a continent, immediately changing the radiation, heat and moisture exchange of the surface (Walsh, 1984). Subsequent aging of the snowpack, and its melting and contamination by pollutants, will produce other equally important if more gradual changes in its radiative and thermal properties. On a longer time scale, the average winter snow cover in the northern hemisphere varied from 16% (of the total hemispheric surface area) in 1970 and 1981 to 19% in 1978 (Foster and Rango, 1982), and Eurasian snow cover has shown 10% variations above and below its average value during the past two decades (Walsh, 1984). Changes in snow and ice cover give rise to two

types of positive feedbacks (Robock, 1983). With rising temperature, the albedo of the surface decreases due to changes in the physical structure of the snow and ice, and a decrease in the area of coverage, revealing darker land or water surfaces. Both of these changes increase solar radiation absorption, and thus enhance the warming.

Birchfield and Wertman (1983), using an energy-balance model, found that the topography of the mid-latitude high-altitude plateaus tended to enhance the positive albedo-temperature feedback. Similarly, Huang (1985) used numerical simulation to assess the teleconnected effects of changes in the heat source of the Tibetan Plateau on mid-latitude circulation patterns. He found that an enhancement of the Tibetan Plateau heat source produced positive geopotential height anomalies over Tibet, the Okhotsk Sea and northeastern North America, and negative height anomalies over northeast China and Alaska. Hahn and Shukla (1976) found an inverse relationship between Eurasian snow cover and Indian monsoon rainfall--i.e. winters with little snow were followed by summers with above average rainfall. Cerveny et al. (1987) compared a 10-year record of South American snow cover with the Southern Oscillation Index (SOI) and found significant inverse correlation, i.e. low SOI was associated with extensive snow cover and vice versa. They postulated that warm events (low SOI) acted to increase winter snowfall. Ross and Walsh (1986) used both observational data and numerical modelling analyses to test the sensitivity of North American cyclones to observed variations in snow and ice cover. They found significant effects on both the intensification and trajectories of winter-time synoptic events. This suggests that forecasts of weekly or monthly circulation patterns may be improved by consideration of observed snow/ice anomalies. On a shorter time scale, Walsh (1987a) investigated effects of snow cover by examining actual synoptic events and found that extensive snow cover favoured rapid intensification and northward motion of cyclones along the east coast of North America.

2.3.3 Soil moisture

Changes in soil moisture affect the albedo and thermal diffusivity of the soil and the Bowen ratio (the ratio of the sensible to latent heat fluxes) in the surface boundary layer. Thus, as a moist soil surface dries out, more of the incoming solar energy is reflected, and a larger fraction of the absorbed energy is used to heat the air (Caborn, 1973). The

heat flow into the soil increases at first, then decreases as the soil becomes very dry (Rose, 1966). The concept that drought begets drought was proposed by Namias in 1960, who supported it with empirical evidence. His analysis of synoptic charts and contingency tables suggested that dry conditions in spring favour the formation of anticyclonic pressure conditions over the area, thus perpetuating the dry conditions for a season, or even longer. Two decades later, numerical modelling studies by Mintz (1982) and Shukla and Mintz (1982) confirmed that there are important effects of soil moisture on local precipitation and on atmospheric circulations. Subsequent simulations (Rind, 1982) demonstrated that spring-time soil moisture has significant effects on early summer surface air temperatures, and is thus a necessary forcing function to be considered in STCP. Fennessy and Sud (1983) examined monthly precipitation values over the contiguous United States, in relation to antecedent monthly precipitation, soil moisture and evapotranspiration. Their correlation analysis suggested that "large-scale droughts over extended periods may be partially maintained by the feedback influence of soil moisture on rainfall". These results were substantiated for African drought, by simulations of the British Meteorological Office climate model (Rowntree et al., 1985). A comprehensive review of the subject was prepared by Mintz (1984), who concluded that changes in soil moisture or surface albedo produce large changes in climate, at the local and regional scales at least.

Van den Dool et al. (1986b) summarized statistical evidence of an apparent relationship between summer-time temperatures and precipitation in the United States. They used a multiple linear regression approach to separate the contributions to temperature persistence from large-scale circulations and local conditions. For the Canadian Prairies in summer, the overall month-to-month correlation was relatively slight and negative (i.e. positive temperature anomalies correlated with low precipitation anomalies). The large-scale circulation contribution ranged from moderately negative in the southwestern Prairies to moderately positive in the east, while local effects were very slight and positive throughout the region. This confirmed the study of Villmow (1956), who found an average growing-season temperature anomaly, during drought years, of +1 to +2°C over the Canadian Prairies. Robertson (1974) found significant negative correlations between monthly values of precipitation and maximum temperature, throughout the growing season, with r values

ranging from -0.24 in June to -0.60 in August. An analysis by Karl (1986) confirmed the importance of the short-term climatic effects of soil moisture and stressed the need for its routine monitoring. Numerical simulations by Ookouchi et al. (1984) and Anthes and Kuo (1986) demonstrated the importance of soil moisture availability in generating mesoscale and synoptic-scale circulations. The difficulty of interpreting numerical simulations of soil moisture effects was demonstrated by Mitchell and Warrilow (1987) who found that the effects may be diminished, or even reversed, by altering the soil physical properties and treatment of run-off over frozen ground in the model.

2.3.4 Other boundary forcings

In the absence of the biosphere, the earth's surface would undergo few changes likely to affect climate on a time scale of a few weeks to a few years other than those discussed above. The biosphere, however, responds strongly to temperature and moisture conditions, and alters many surface feedbacks by modulating surface albedo (Mintz, 1982) and emissivity, aerodynamic roughness (Sud and Smith, 1985), and moisture availability (Bolin, 1984). Other, perhaps lesser, effects include protection of the soil from erosion and modification of its properties (through root systems), changes in surface-water properties caused by plant growth in aquatic ecosystems (Venrick et al., 1987), and production of biogenic condensation nuclei (Bates et al., 1987). An analysis of many of the processes involved in biosphere/atmosphere interactions may be found in Dickinson (1983), and simulations of the effects of varying some of them have been carried out by Wilson et al. (1987).

Most studies of human impacts on climate have tended to look at either small-scale or long-term effects (Kellogg, 1977 and 1978), mainly related to such things as atmospheric pollution, urban development, agriculture, and the large-scale clearing of forests. Cess (1978) suggested that a biosphere-albedo feedback would roughly double the sensitivity of the global climate system factors which produce climatic change.

There may also be effects on shorter time scales (Kellogg, 1979; Ripley, 1987). Using numerical simulations, Sud and Smith (1985) found that local increases in surface albedo and reductions in surface roughness (as would result from removal of forest) had a weakening effect on the Indian monsoon.

Similar reductions in precipitation were found for the Sahara desert by Sud and Fennessy (1982) and Sud and Smith (1985). Handler (1985) found a statistical relationship between atmospheric aerosol concentration and U.S. crop yields, which he ascribed to the aerosols influence (through solar radiation absorption) on the equator-to-pole temperature gradient, and hence atmospheric circulation.

2.4 External forcings

Major volcanic eruptions eject materials as high as the stratosphere, and apparently may cause reductions in surface temperature of several tenths of a degree that persist for as long as several years (Kelly and Sear, 1984). Robock (1985b) detected volcanic signals in the Russian air temperature data set, with peak responses occurring 2-3 years after the events. Greatest cooling was found at high latitudes during the winter. Some cooling was found at all latitudes and seasons, except in the Arctic during the summer. Sear et al. (1987), on the other hand, found shorter lag times, ranging from near zero in the same hemisphere to 6 months to a year in the other hemisphere. After removing ENSO effects, Parker (1985) was unable to find any conclusive evidence of cooling of the tropical troposphere following the 1963 Mount Agung and 1982 El Chichon eruptions. The effects of volcanic dust veils on climate elements other than temperature have been discussed by Lamb (1970). Skinner (1985) investigated the possible effects of volcanic eruptions on Canadian climate, by comparing values of climatic parameters, from a number of stations for several volcanic events, from several years before an eruption to several years afterwards. He found temperature depressions between 0.4 and 1.0°C lasting up to two years or so after the event, and also noted less conclusive decreases in precipitation of about 5 mm on the Prairies during the eruption year and that following.

There is a consensus that the increasing concentrations of many radiatively-active gases in the atmosphere, such as water vapour, carbon dioxide, methane, etc., will lead to a warmer, and probably more humid, global climate. A discussion of the modelling evidence and potential effects on Canada as a whole may be found in Brown and Walsh (1986) and in Ripley (1987). Possible effects on Saskatchewan agriculture have been analyzed by Williams et al. (1987). While the greenhouse signal has not yet been confirmed (Parker, 1986), a recent analysis of an Antarctic ice core (Genthon et al., 1987)

indicated that carbon dioxide may have played an important climatic role during the late-Pleistocene. There is evidence from tree-rings and other sources that the current increase may already be having measurable effects on the biosphere (Lamarche et al., 1984; Lachenbruch and Marshall, 1986; Enting, 1987).

Part 3. Drought Forecasting

The focus of this chapter will be on short-term climate prediction (STCP) of precipitation and temperature. It will be assumed that predicted values of other indicators of drought, such as the PDI, soil moisture content, river flows, etc. can be derived from a STCP through the use of appropriate modelling procedures, such as that presented by Lehman (1987).

The general problem of atmospheric predictability will be discussed first, followed by a review of the various approaches to STCP and an assessment of their current skill levels, and finally an examination of each of the approaches in more detail with regard to the state-of-the-art and future prospects. This assessment is based on a number of recent reviews of long-range forecasting (Barnett and Somerville, 1983; Shukla, 1984a & b; Gilman, 1985; Namias, 1985; Chervin, 1986; Gilchrist, 1986; Somerville, 1987), supplemented by personal visits to research and forecast centres in Canada, the U.S.A. and Great Britain, during which many experts in the field of STCP were consulted (see Appendix A).

3.1 Predictability

There is general agreement that the limit of deterministic weather predictability is a few weeks at most (Hoskins and Sardeshmukh, 1987). This is largely because, due to limited sampling, there will always be an incomplete knowledge of the atmosphere's initial state (Gilchrist, 1986). Adding to this problem are measurement errors and imperfections in our understanding of atmospheric processes (Somerville, 1987). While the last two weaknesses may be improved in future, the first is almost intractable, and these initial errors will grow during the model simulation until they overshadow the initial signal. This is illustrated diagrammatically in Figure 9 (Anthes and Baumhefner, 1984), where the relative contributions, to predictability, of initial data and processes (models) are expressed as functions of time.

Considerable attention has been given in recent years to the development of a theory of predictability (Leith, 1978; Lorenz, 1982; Leith, 1983; Shukla, 1984). This will guide forecasting effort by showing what can, and what cannot, be predicted. While most of this work has been devoted to deterministic forecasting (Somerville, 1987), STCP has received some attention (Madden, 1981; Chervin, 1986). Beyond

the deterministic limit, as boundary forcings play an increasingly important role, the only evidence of predictability comes from empirical and statistical sources. These indicate that predictability may exist at longer time scales in some cases but not in others (Nicholls, 1980; Barnett and Somerville, 1983; Chervin, 1986). Chervin's study showed potential predictability for 70 kPa geopotential height for the eastern Prairies during the summer season and for all of the Prairies during the winter.

Situations that are more predictable include persistent anomalies such as blocking (Bengtsson, 1981; Leith, 1983; Dole, 1986). While the short-term predictability is greater in the mid-latitudes than in the tropics, the reverse appears to be true for longer-period climatic variations (Shukla, 1984a & b; Hastenrath, 1986; Rasmusson, 1986). Many of the problems associated with long-range predictability were reviewed by Barnett and Somerville (1983), who stressed the importance of maintaining credibility of climate forecasts through an adequate and well-advertised verification scheme. Recent work by Nicolis and Nicolis (1984), Lovejoy et al. (1986) and Fraedrich (1987), indicates that predictability may be deduced from phase-space trajectories of climate variables that evolve on attractors.

Davis (1978) used seasonally-stratified statistics to look for relationships between sea-level pressure (SLP) and SST over the North Pacific. He found that SLP anomalies in the fall and winter were predictable from prior observations of either SLP or SST, using linear models. However, this was not the case in the spring and summer. Barnett (1981) used a similar approach to investigate relationships between surface air temperatures over North America and North Pacific SLP and SST. The highest predictive skill was found for the west coast and for southeastern N.A., where about 20% of the variance was explained by the predictors. Madden (1981) analyzed a long series of temperature records to estimate the potential predictability of seasonal temperatures in the U.S. He found that about 60% of the variance of winter means were predictable on the northeast and southwest coasts, dropping to less than 20% over much of the Great Plains. The states bordering on the Canadian Prairies showed predictabilities increasing from about 20% in the west to 50% in the east.

A group of meteorologists attending the Study Week on "Persistent Meteo-Oceanographic Anomalies and

Teleconnections", held at the Vatican in September, 1986, assessed the present limitations of both numerical and empirical weather forecasts, together with prospects for future improvement (Fig. 10). They assessed the current limit of numerical/dynamical weather predictions to be about one week, with the possibility of future improvement to 2-3 weeks. Climate predictions, on the other hand, were considered to be most skillful at present in the tropics, for a one season time frame. Future improvements are likely by extension to the extra-tropics, and to both shorter and longer time periods. The group "concluded that there is a considerable hope for predictions of some of these episodes (teleconnected surface boundary forcings such as ENSO) with a useful level of accuracy in the not too distant future" (Pontificiae Academiae Scientiarum, 1987).

3.2 Current skill

The most recent policy statement of the American Meteorological Society on weather forecasting (American Meteorological Society, 1983) assessed the current skill of the profession in producing short, medium and long range forecasts. They attributed considerable skill to the shorter-range forecasts, with skill decreasing from good at three days to fair at five days, with some skill out to ten days, in the case of temperature. For precipitation, the skill was assessed at fair for three days decreasing to only marginal for five days. Monthly and seasonal forecasts were considered to have slight skill only in the case of temperature. However, they were optimistic that some improvement in predicting monthly and seasonal averages would emerge from present research on large-scale, ocean-atmosphere interactions. Namias (1978) quantified predictive skills for monthly and seasonal temperature at 61% and 58% respectively, where chance would be 50%. He estimated skill values for precipitation to be about 5 percentage points less.

The skill of short-range weather forecasts has been steadily improving over the past two decades, largely as a result of improvements to numerical models. A comparison of forecast errors of a number of models (including Canada's) between 1979 and 1986 illustrates this general trend, as well as the strong seasonal effect (Fig. 11). Those of the following studies, that were carried out a few years ago, should be interpreted in light of this recent improvement.

U.S. medium-range weather forecasts were assessed, over the 1978-81 period, by Guaraldi and Bosart (1985). These forecasts were prepared using a combination of numerical and subjective techniques, and predicted temperature on a 5-class scale and precipitation on a 3-class scale. The temperature forecast showed slight skill (approximately 5 percentage points better than climatology), with the skill confined mainly to the two extreme classes. However, a forecast of persistence did almost as well. No skill was found in the precipitation forecasts.

A number of monthly forecasting methodologies were tested in Europe by Nap et al. (1981). These included those used by the U.S. National Meteorological Center (NMC), the United Kingdom Meteorological Office (UKMO), persistence, an analogue method, a multiple-regression method, one using transition rules (to be described in Section 3.3.3), and one based on SSTs. None of the methods was very successful when tested for the 1970s. Of the elements tested (temperature, precipitation and sunshine), only mean temperature showed measurable skill. While all methods showed some positive skill, only the results for the transition rules and SSTs were found to be significant.

A nine-year record of seasonal temperature and precipitation anomaly forecasts for the United States was analyzed by Preisendorfer and Mobley (1984). Four subjective forecasts, made by Jerome Namias, Donald Gilman and colleagues, Art Douglas, and Tim Barnett and Rudolph Preisendorfer, using a variety of methods, were compared with persistence, climatology, and a random forecast. The subjective forecasts were generally better than the random and climatological forecasts, but often no better than persistence. Highest scores were achieved for temperature forecasts in the southwestern desert region. The authors concluded that the current level of seasonal forecast skill was "not adequate for anything more than educated speculation". Namias (1981b) found that seasonal temperature forecasts (1958-80) for the U.S. showed considerable spatial variation. Winter forecasts showed greatest skill in the southwestern desert and the southeast, followed by the northwest and north-central part of the country.

Monthly forecasts of temperature, precipitation and sunshine for the United Kingdom were considered to have shown improvement during the late 1960s (Ratcliffe, 1970). However, subsequent results led Jolliffe and Foord (1975) to assess the

forecasts as being largely unsuccessful. Skill scores for the UKMO monthly temperature forecasts, based mainly on analogues, showed no improvement during the period 1965-80, and on average were lower than persistence forecasts (Nicholls, 1982).

The Canadian Climate Centre began issuing monthly and seasonal forecasts of temperature and precipitation (monthly only) anomalies, on an experimental basis, in early 1985. Based on a number of methodologies (NWP, analogues, extrapolation, time series, regression equations, and persistence), and using specification equations to relate 50 kPa height anomalies to surface temperature and pressure anomalies, the forecasts showed measurable skill for monthly temperature only (Newark et al., 1986; Atmospheric Environment Service, 1987). The introduction of an objective technique (empirical orthogonal function filter) for producing height anomaly fields produced a skill score of 71% (compared with 61% for persistence and 58% for the subjective technique). Introduced initially for an 18-month period (Shabbar, 1985; Shabbar and Knox, 1985), the program was subsequently extended to July, 1987. Since then, issue of the precipitation forecast has been dropped and that of temperature extended to the general public.

Dixon and Harnack (1986) used the principal components of the tropical and North Pacific SST fields as predictors, in a "jacknife" regression approach, to predict area-averaged temperature anomalies for U.S. winters separated on the basis of intraseasonal variability. The "jacknife" or "cross-validation" approach permits independent testing, in spite of small sample size. Dixon and Harnack found statistically-significant skill in a run of 30 years data, with a tendency for higher skills in years with lower intraseasonal variability. This result is consistent with the observation that long-range predictability is often greater in summer than winter (Madden, 1977).

Statistical relationships between Sahel rainfall and world-wide SST anomalies a season earlier were used by Folland et al. (1987) to forecast summer precipitation for 1986 and 1987. The 1986 forecast appeared to be skillful, with the observed rainfall being 68% of average, compared with a forecast value of 75%. A similar forecast for 1987 also appears to have been successful (Folland, 1987).

3.3 State of the art

The numerous methods of making STCPs have been summarized by Schneider (1978), Wilhite (1980), Namias (1981b), Nap et al. (1981), Shabbar (1985) and Beran and Rodier (1985). The simplest approach to forecasting is to predict the continuation of current conditions. While hardly deserving to be called a forecast "method" (Nap et al., 1981), persistence is often used as a standard against which the results of other methods are compared. Evidence of persistence in many climatic parameters was discussed earlier, and the subject was reviewed in relation to drought by Beran (1979), who attributed its occurrence to teleconnections of persistent circulation anomalies caused by anomalous boundary forcings. If useful relationships can be established between these circulation anomalies and their forcings, then this type of persistence becomes potentially predictable.

The next approach, in order of increasing sophistication, is the actuarial method, sometimes referred to as a climatological method. It is merely a statement, based on simple statistical analysis of past data, of the probabilities of certain types of weather occurring in the future.

The analogue approach also uses historical data, but of the genetic rather than the empiric type. This involves searching a large database of past synoptic charts to find the best analogue of the current situation. Both subjective and objective methods are used to recognize analogues.

The purely statistical approach covers a broad range of potential predictors, which may not have any quantifiable physical relationships with the predictand. This can include the use of trends, extrapolations, contingency tables and cycles, and the statistical methodology can vary from simple linear regression to canonical correlation.

The statistical-physical approach differs from the above in that physical relationships are known to exist between predictand and predictor, but these relationships are too complex or tenuous to be defined deterministically.

The final approach is, some would say, the only proper approach--the simulation of atmospheric dynamics using computer modelling techniques.

Of course, permutations and combinations of the above methods may also be used to produce the final forecast. Alternatively, forecasts may be made by several methods, and the consistency of the results used to assign a confidence level to the forecast. It has been found (Jones, 1987) that forecasts issued with a high degree of confidence have superior skill scores compared with those issued with lower confidence values.

3.3.1 Actuarial methods

The simplest types of actuarial forecasts (Schneider, 1978) are merely statements of the probabilities of occurrence of certain events, such as precipitation amounts being greater than, or less than, a specified amount. These can be made more useful by combining them with drought indices, such as the PDI or CMI. Since most indices are cumulative, they can be computed using actual data up to the present with future values being based on climatological probabilities. Thus, probabilities may be expressed as PDI or CMI values having certain values a month or more in the future, and these can be updated on a regular basis. This method was used by Cordery (1987) with a water balance model for dryland farming conditions. It required inputs of precipitation, potential evaporation, and soil hydraulic properties, and produced probabilistic outputs of the water-balance components and crop yield. Another use of this approach is the specification of probabilities of amelioration or termination of an existing drought situation. Karl et al. (1987) used the PDI in a forecast mode, together with precipitation probabilities for one, two, three, and six month periods to examine drought termination probability in the continental United States. They found that the annual precipitation cycle and the skewness of the precipitation distributions were the main factors influencing drought amelioration and termination. Once a serious drought was underway, the probability of amelioration or recovery within one or two seasons was low, especially in the interior of the country.

3.3.2 Analogue methods

This approach consists of a search of historical synoptic charts to find one or more analogous situations, according to specified criteria. The weather developments in these historical cases are then used as the basis for the current prediction. This method has the advantage that it uses actual

past cases, and thus incorporates all of the existing complexities into the weather prediction.

The analogue approach requires a well-organized file of historical records, covering as long a period as possible. The selection of analogues may be done subjectively or objectively, and matches may be made for different meteorological parameters, different areas of comparison, different seasons of the year, different levels of the atmosphere, and for a single point in time or a time series. The most-commonly used objective measures of similarity are the minimization of root-mean-square differences and the maximization of spatial correlations or covariances (Shabbar and Knox, 1985). While these methods have been applied mainly to pressure or geopotential height charts, a new perspective might be introduced by applying them to satellite-sensed cloud patterns.

For short and medium-range weather forecasting, the analogue approach has been largely replaced by numerical methods, but it is still widely used for STCP. A multifield analogue scheme (using 70 kPa height, 70-100 kPa thickness, SST, precipitation and surface air temperature) for STCP was described by Barnett and Preisendorfer (1978). A series of three metrics (defined by the current state, the evolution of the current state, and a combination of the two) assigned to the multi-dimensional hyperspace of the climate state vector, was used to select analogues. Forecasts were evaluated for both spatial and temporal skill. A test for North America, with a 24-year database, indicated the existence of significant predictive skill, particularly in the summer season, and that analogue methods might be used to produce useful climate predictions up to four seasons in advance.

Nap et al. (1981) described a long-running analogue approach used by the Dutch Weather Service. Daily weather maps since 1881 are searched for analogue years in which the evolution of atmospheric circulation types over Europe resemble the current situation during a period of at least a few months. The method has been used to predict temperature, number of dry days, and sunshine. The main difficulty is in finding a good analogue. There are usually several mediocre ones which often show divergent future behaviour. In a comparison with a number of other methods, Nap et al. (1981) found that this time-consuming analogue approach did not fare as well as simpler statistical approaches.

Shabbar and Knox (1985) examined the analogue approach to forecasting 50 kPa heights up to a month in the future. Using a system of variable weightings for the current and historical (up to 10 days) states, and several methods of analogue selection, they found that even "the... 'top' analogues, based on an objective ranking system, have less predictive skill than persistence", when the current persistence level is high. However, when current persistence is low, the top analogues gave a better forecast. They also found that there was usually a "best" analogue among the top ten, which always scored higher than persistence. The problem, however, is to determine which is the "best". Shabbar and Knox expressed the hope that other pattern recognition methods, such as principal component analysis, may give better results.

Some potential difficulties in the assessment of skill of analogue forecasts have been described by van den Dool (1987). These relate to cross-validation methods in which the verification data were not withheld from the developmental data, and may have produced erroneous results in many published reports.

3.3.3 Purely statistical methods

There are a large number of statistical approaches to weather and climate prediction. Those with a physical basis will be treated in the following section, while the remainder will be discussed here.

Regression analysis has been used for both monthly and seasonal climate predictions (Namias, 1981b). The methods that have been applied range from simple linear regression to stepwise multiple regression and even empirical orthogonal functions. Forecasts are derived from the regression analyses by means of extrapolations of trends and periodicities found in the historical data. The predictors may include: present and past values of pressure, temperature, wind, snow cover, and even sunspot number or other cyclic variables. Temperature, pressure, precipitation or a drought index may serve as predictands. The Canadian Climate Centre (Shabbar, 1985) uses an auto-regressive-moving-average (ARMA) technique as one of the methodologies in its monthly forecasting procedure. It predicts grid values of the 50-100 kPa thickness anomalies from the previous month's values and forecast errors for the present month. In general, little success can be expected from such procedures because of the high level of

randomness in climate series (Beran and Rodier, 1985), and the low probability of finding internal cycles in the atmosphere (Tapp, 1984).

Contingency charts and tables (Namias, 1981b; Beran and Rodier, 1985) express the probability of an event in a given class interval occurring at some time in the future, contingent on the present situation. The method is similar to, but more flexible than, the use of persistence. For example, historical data may be analyzed to determine the probabilities of warm, cold or normal months following warm, cold or normal months. These types of analyses may be carried out for various weather elements, as a function of season, geographical area, and lead time. The results are then used to prepare probability forecasts. Gordon and Wells (1976) applied the method to monthly temperatures in central England, using a quintile distribution. They found the best correlations between the months of February and March and from June to September, while the poorest periods were April to May and November to December. Cold anomalies appeared to be slightly more persistent than warm anomalies. The correlation dropped quite rapidly after one month with only a slight positive correlation remaining at six months. A slight negative correlation appeared at a lag of 12 months, presumably related to the QBO. They claimed the method was at least as good as the analogue approach currently in use by the UKMO. Their results were substantiated by Nap et al. (1981) who compared the approach (which they termed 'transition rules') with a number of others for the prediction of monthly temperatures in western Europe. Correlations of 70 kPa height anomalies of one month with the next, over the northern hemisphere, were examined by Van den Dool and Livezey (1984). In general, correlations were 0.3 or greater at low latitudes, but less than 0.2 at mid-latitudes. For the Canadian Prairies, values were highest in the winter (> 0.2) and spring (0.10-0.20), dropping to less than 0.10 in summer and autumn.

Van Loon and Jenne (1975) tested three statistical methods of estimating the next season's average temperature in a region of the U.S. (New England) where the season-to-season temperature correlation is highest. The three methods: contingency tables, regression equations and trend analysis all achieved a moderate amount of skill in this exceptional case. They concluded, however, that "the degree of association between two seasons which made this modest improvement possible is comparatively rare at extratropical latitudes".

Historical SOI data were analyzed by Chu and Katz (1985), using a stochastic-modelling approach. Auto-regressive-moving-average processes were applied to model and predict the SOI on a monthly and seasonal basis. The prediction success was reasonable, considering that only historical SOI data are used as predictors. However, the model has other potential uses, such as the production of simulated SOI time series for use in teleconnection studies. It was recently used to calculate the predictability of the SOI on monthly and longer time bases (Chu and Katz, 1987). Although predictability decreased with lead time, reaching near zero after three to four months, forecasts for the following season tended to be more successful (53%) than those for the following month (44%).

Christensen et al. (1981) applied a multivariate analysis system based on information theory to the production of annual hydrological forecasts for central California. This "entropy minimax" method used a large number of historical data variables, including precipitation, temperature, pressure, SST, etc. at numerous sites, to predict precipitation in the region a year ahead. The method showed significant skill in predicting wet or dry (above or below median) conditions. Further validation tests (Eilbert and Christensen, 1983) confirmed that the model predicted the correct category 67% of the time, and established that the result was significant at the 98% confidence level. There was also an indication that dry years were more predictable than wet years. This work was subsequently extended to western Oregon and eastern Washington (Christensen and Eilbert, 1985), with results of 74 and 69% accuracy, at 99 and 97% confidence levels, in the two regions respectively. The authors concluded that this method could predict winter precipitation, at six month lead time, with statistically-significant skill. This method is currently being tested by the Canadian Climate Centre (Atmospheric Environment Service, 1987).

3.3.4 Statistical-physical-synoptic methods

The main approaches that will be discussed in this section involve teleconnections and boundary-forcing effects in general, as well as persistent atmospheric circulation anomalies such as blocking. Most of these approaches will someday be replaced by improved numerical models, incorporating more realistic boundary parameterizations and completely coupled oceanic models.

Teleconnections are expressions of the inter-dependence of the atmospheric circulation at one point (on the earth) and the circulation, and boundary forcing, at another point. Charts have been drawn that show the correlation between geopotential height anomalies at any reference point and all other grid points over a hemisphere. An example is that of Namias (1981a) for the northern hemisphere 70 kPa height. Charts for each season show the correlations between reference points on a 5° latitude and 10° longitude grid and every other point in the hemisphere. Dunn (1983, 1984) separated out positive and negative anomalies to produce teleconnection charts for the summer and winter seasons at the 50 kPa height. Stratification by sign permits the detection of non-linear relationships between positive and negative height anomalies that are not revealed by linear correlation based on the entire sample of data. Another set of 70 kPa charts has recently been prepared by Wagner and Maisel (1987) using sign stratification. They are presented for each month, but were calculated using four two-week periods starting a half month before and ending a half month after each month. This increased the number of data points and optimized the statistical significance of the results while still capturing the seasonal variation.

The use of teleconnections in STCP has been summarized by Namias (1981b), Shabbar (1985) and Beran and Rodier (1985). Rather than providing firm forecasts, the method is most often used as a subjective aid in the preparation of a STCP. Teleconnection charts permit a forecast to be extended from one area, where a high-confidence forecast may be possible, to another, where it may not be.

The importance of boundary forcing in determining atmospheric behaviour increases with the passage of time, surpassing initial conditions after about a week. While all anomalous conditions, such as snow and ice cover, soil moisture, etc. play a role, those of the oceans, by virtue of their two-thirds coverage of the earth's surface are undoubtedly dominant (Fig. 8).

The much longer time constant of the oceans, compared to the atmosphere, is responsible for a good deal of the month to annual scale persistence that the climate system exhibits. Partly because of this, the macroscale thermal characteristics of the sea surface appear to be easier to predict, over periods of a month to a season, than atmospheric motions. This has led to the development of a method of STCP, based on

large-scale air-sea interactions (Namias, 1981b; Namias and Cayan, 1981). Basically, this involves predicting changes in oceanic thermal patterns, and establishing relationships between oceanic and atmospheric anomalies. The predicted oceanic regime is then used to produce an atmospheric forecast by means of these established relationships, together with teleconnection information. This method has been applied to the use of North Atlantic SST anomalies to predict the next month's temperature anomalies in Europe (Nap et al., 1981). The method achieved higher skill scores than a number of other statistical procedures, for a series of forecasts over an eight-year period (Ratcliffe, 1971).

The strong influences of ENSO on many tropical and extra-tropical weather phenomena indicate its potential importance for STCP (Namias and Cayan, 1984). If ENSO events can be predicted months or seasons in advance, and if their teleconnected effects can be quantified, then this will indeed become an important tool for STCP. Inoue and O'Brien (1984) developed a statistical-physical procedure for predicting the onset of a major El Niño one to three months in advance from shipboard observed winds. A test of their model showed that it would have detected the onset of the 1982-83 event several months before it was actually noticed. They also applied their procedure successfully to the prediction of the decay of the same event (Inoue and O'Brien, 1986). A numerical approach to forecasting El Niño events will be described in the next section.

In the summary of his review of "The Global Atmospheric Circulation and Weather Forecasting", Pearce (1985) gave examples of problems which need to be addressed by numerical model simulations. One of these was the question "to what extent are persistent (blocking) patterns in mid-latitudes determined by large-scale oceanic forcing through sea-surface temperature anomalies in low and middle latitudes?". Drought in the Canadian Prairies is often related to blocking events (Knox, 1982). While blocking is usually a naturally-occurring internally-generated feature of the atmosphere (Blackmon et al., 1986), it may also be boundary-forced by SST anomalies (Shukla, 1986). Although it has been clearly demonstrated that a major tropical SST anomaly, such as El Niño, can have significant effects on both tropical and mid-latitude atmospheric circulations, the effects of mid-latitude SST anomalies are still ambiguous. Results obtained from both diagnostic and numerical modelling studies (Shukla, 1986) are

conflicting. This tends to substantiate the heuristic notion that such effects are likely to be more difficult to detect because of strong pre-existing wave patterns, due to stationary forcings and dynamical instabilities, in the mid-latitudes.

A statistical-kinematic technique may be used to track and extrapolate slowly-evolving trends in the general circulation (Namias, 1981b; Beran and Rodier, 1985). This highly-subjective method may be used to supplement other forecasting tools. It involves examination of time-averaged circulation patterns over a period of several weeks or months, and then extrapolating them ahead to the forecast period. Kinematic considerations may suggest that current trends will continue, or that new developments will occur. For example, if a trough and the next upstream ridge are moving apart, a new perturbation might be expected to form between the two. After predicting a new circulation pattern, temperature and precipitation fields may be derived from it using specification equations (Klein, 1983; Klein and Bloom, 1987).

3.3.5 Simplified-dynamics methods

According to Tapp (1984) "the inherent variability of the atmosphere is very much larger than the capability of numerical models to predict it". The huge number of degrees of freedom in the atmosphere may be reduced to a manageable level by using simplified-dynamics models with parameterizations. However, this really amounts to a type of statistical approach, and is based on a extremely inadequate length of time series of data. The following two cases are recent examples of such models that have achieved some measure of success in STCP. While simplified-dynamics models are simple to build and understand, and cheap to run, their coarse treatment of time and space scales may be more appropriate to STCP than those of GCMs (Egger, 1982). On the negative side, most of these types of models at present have temperature as the only forecast variable, and usually neglect interactions between atmospheric motions of different scales.

Donn et al. (1986) used a model, based on the first law of thermodynamics, that includes parameterized dynamics for eddy diffusion and horizontal wind transport of heat, to produce numerical predictions of mean monthly temperature anomalies. When subjected to a 93-month test, the model performed at least as well as the U.S. NWS monthly forecast, and

significantly better than chance.

A deterministic numerical model, of the coupled ocean-atmosphere system in the tropical Pacific, was used by Cane et al. (1986) to forecast all El Niño events since 1970. This simplified non-linear model was designed to isolate the physical processes involved in ENSO. It simulates surface winds, SSTs and thermocline depths, and in a simulation study was able to predict El Niño events generally 1-2 years in advance. The authors included a prediction of a moderate ENSO event beginning in the spring of 1986. In spite of many positive signs during the spring (Kerr, 1986a,b), it was not until December that the arrival of ENSO was generally acknowledged (Kerr, 1987). This prompted the question of whether or not this was the same event that had been predicted a year earlier.

3.3.6 Dynamical-numerical methods

Improvements in data collection techniques, mathematical methodology and computing technology have resulted in a steady increase in short-range forecasting skill over the past decade (Fig. 11). Dynamical-numerical methods, in contrast to the empirical methods described above, produce predictions of the instantaneous state of the atmosphere at some time in the future. The present limit, due to the growth of initial uncertainty with time, is about one week (Simmons, 1986; Kasahara, 1987). However, this should be extendible to at least ten days (Lorenz, 1982), and the lower frequency components of the variability may be predictable up to several weeks ahead (Shukla, 1981). Realization of that predictability requires a probabilistic approach through the averaging of simulations with respect to space, time or ensemble (Daley and Chervin, 1985; Kasahara,1987). Roads (1986) considered the effect of averaging the more-accurate early days of a NWP forecast with the less-accurate later days, and found useful forecast intervals for time averages to be about twice the useful forecast intervals for instantaneous events. Owen and Palmer (1987) compared the skill of 90-day ensembles in assessing the impact of El Niño, using the UKMO 11-layer GCM. In the tropics, skill at predicting 20 kPa heights was improved at all time-scales while in the extra-tropics, there was general improvement although not consistently at the shorter time-scales. Their results were consistent with those of Palmer (1987) that SST anomalies have a consistent impact of forecast skill in the tropics, but that a longer averaging

period is required in the extra-tropics.

Short-Range Weather Forecasts

Numerical methods have progressed to the point where they can produce highly-accurate forecasts in the mid-latitudes three days ahead (Pearce, 1985). The major weakness of such methods relates to the prediction of extreme events (such as very heavy rain or snowfalls, or high winds) which are usually very localized, i.e. below the models' resolution (Kasahara, 1987). However, model modification to accomodate fine-mesh grids over the target regions has met with some success.

Medium-Range Weather Forecasts

Numerical weather prediction has been focussing on the 4 to 10 day range during the past decade. High resolution models, covering the entire globe, are necessary to cope with this time span, for which one of the main challenges are the prediction of change-overs from one weather pattern to another (Pearce, 1985). Substantial improvement in skill has been achieved in this range, and further modest gains are likely in the next few years, mainly through "a systematic and meticulous improvement of all aspects of the forecasting system" (Bengtsson, 1984).

Long-Range Weather Forecasts

Beyond a week or so, the initial conditions become less important than the boundary forcings. Both, however, have to be considered up to a month (Gilchrist, 1986). Beyond that, only the boundary forcings are relevant. The future of numerical methods in this range is clearly dependent on the development of better parameterizations of physical processes within models, particularly with respect to surface boundary processes (Mintz et al., 1983; Dickinson, 1983).

Extended-Range Weather Forecasts

Although the predictability of individual weather systems disappears after a week or so, there are indications that useful predictions of averages can be made, perhaps, for periods of up to a month or more (Bengtsson, 1984; Reinhold, 1987). Beyond this range, errors in the initial conditions contaminate the forecasts of even the largest scales of atmospheric motions (Walsh, 1982). Several of the major

numerical modelling centres around the world are now involved in a dynamical extended-range forecasting (DERF) program that has the goal of extending numerical forecasts to the limit of dynamical predictability (Gilman, 1986).

3.4 Operational forecast methodology

Canada

Initially, Canada's long-range forecast program was experimental, with the products being distributed to about 150 potential users (Shabbar, 1985; Atmospheric Environment Service, 1987). The monthly and seasonal forecasts are essentially subjective, with objective guidance. The general approach is to forecast the 50 kPa height anomalies, and then to deduce from these surface temperature and precipitation anomalies. The actual procedure involves predicting the location and sign of the main northern hemisphere height anomalies, using teleconnection charts, current anomalies and the latest extended-range numerical forecasts. Next the remainder of the height field is filled in. This was formerly done subjectively, but more recently an objective procedure with an empirical orthogonal function spatial filter has been used. Finally, anomalies of surface climatic parameters are derived from the upper-air anomalies using either a subjective approach (formerly) or specification equations (more recently).

United States

Monthly forecasts are prepared by one person, starting with the latest numerical 70 kPa prognostic anomaly charts (Nap et al., 1981; Preisendorfer and Mobley, 1984; Gilman, 1985; Livezey, 1987). Observed trends are projected forward a month, with anomalies being adjusted so that they are consistent with teleconnection patterns. Alternatively, pattern analysis may be used to separate different circulation types, persistence and changes. A forecast height anomaly chart is drawn, and from this a surface forecast chart is derived. Through the use of statistical auxiliaries, such as contingency tables and consideration of local effects, a forecast is arrived at, and converted to probability format.

Seasonal forecasts, on the other hand, are prepared by four persons independently, and then combined in conference (Gilman, 1985; Livezey, 1987). Simple empirical techniques are

used to predict temperatures, from which a precipitation forecast is derived by the use of analogues. Up to two years of lagged height correlations are available, as are teleconnection charts, for reference. Southern Oscillation Index correlations may be incorporated in the near future. An optional analogue prediction system is also available.

Great Britain

Since 1981, long-range forecasts in Great Britain have been issued only on an experimental basis (Gilchrist, 1986; Jones, 1987). Their preparation is based on a number of statistical techniques, including cluster and discriminant analysis. Most recently, the 30-day forecast period has been divided into three periods. The numerical forecast is used for the first five days; a combination numerical/statistical approach is used for the next ten days; and a purely statistical method for the final fifteen days. The statistical method used at present is multi-variate analysis. In each case, the initial prognoses are surface isobaric charts. These are prepared initially by one person, than discussed by a group of five to ten persons until a consensus is reached. Regression relations are used to convert the pressure charts to temperature and precipitation forecasts, which are then expressed as probabilities. An interesting aspect is the assignment of confidence scores (highest-A to lowest-D) to each forecast. Although A has never been used, and B only rarely, forecasts issued with a C rating tend to more skillful than those rated D or E.

Germany

The German Weather Service uses a multiple-regression technique, with a large number of predictors (Nap et al., 1981). Historical analogues also may be involved. Forecasts are expressed in terms of temperature and precipitation intervals, using flexible class sizes.

Netherlands

The Dutch Weather Service uses the analogue approach to predict monthly mean temperature, precipitation and sunshine (Nap et al., 1981). Data records from 1881 are searched for analogues that persist for at least several months.

3.5 Summary and future prospects

At the present time, there is no completely satisfactory method that can be used routinely to predict mid-latitude climate over the month-to-season time range. Numerical methods are limited to a week or so, and even if DERF is successful, are unlikely to be extended beyond a month. While forecasts for such short periods have little significance for the outbreak of drought, they may be extremely valuable with respect to its termination (Hounam et al., 1975). The main hope for improvement in monthly-to-seasonal forecasts appears to rest on the realistic simulation of the surface boundary conditions (Hoskins and Sardeshmukh, 1987), namely of: soil moisture and vegetation, snow cover, and the state of the oceanic surface layer including sea ice and sea-surface temperatures. Major factors in the improvement of longer-scale numerical predictions will be the coupling of atmospheric and oceanic GCMs, the provision of a more realistic treatment of land-surface processes, and the use of more-sophisticated averaging methods to remove the high-frequency transients from model output.

Many empirical forecast methods now show some long-range skill for temperature, but not for precipitation. Nevertheless, the field is advancing rapidly and great strides have been made in STCP for the tropics and many sub-tropical areas, such as the Sahel (Folland et al., 1987), India (Shukla and Paolino, 1983), northeast Brazil (Hastenrath, 1986), and Australasia (Nicholls, 1982).

As indicated earlier, their greater weather-noise level makes the mid-latitudes more difficult to deal with, but this problem is not insurmountable. Diagnostic studies are revealing many weather patterns that are teleconnected to surface anomalies such as ENSO. A significant characteristic of these anomalies is their persistence (Chen, 1982), making them potentially valuable predictors in long-range forecasting. However, there is increasing evidence that predictability will vary with location, with season, and with synoptic situation (Nicholls, 1982). One important research area will have to be this determination of potential predictability, so that effort will not be wasted trying to do the impossible. This will require extending the work of Chervin (1986), and investigating new ideas such as the climatic attractor approach suggested by Fraedrich (1987).

It is conceivable that some parameters or indices may be more predictable than others. For example, the nature of the processes involved make precipitation a far more difficult parameter to forecast, and verify, than temperature. The existence of a negative correlation between temperature and precipitation, in many drought-prone areas, may make it easier to predict a drought index, such as the PDI or CMI, than precipitation alone. However, a study by Karl (1983) of the spatial characteristics of drought duration in the United States found that although the PDI showed considerable skill as a contingency-table predictor up to 12-months ahead, forecasts using it were not significantly better than those obtained using precipitation itself.

The usual practice of forecasting time-averages instead of instantaneous values, in STCP, has been questioned by Van den Dool (1985). Not only are time-averages much less useful, but such forecasting obscures the distribution of skill through the period. Since most of the skill in longer-range forecasts is to be found in the early part of the period, an extension of the forecast period tends to dilute the skill. He concludes that the only justification for forecasting monthly or seasonal averages is to facilitate statistical skill testing.

A similar concern relates to the forecasting of extreme cases, such as heavy rains and prolonged droughts. There is some evidence that extreme events "cast their shadows well before they take place" (Namias, 1985), and hence may be more predictable than less extreme events. There is no question that weather extremes have greater impacts on society, and that their prediction is more desirable. They may, however, be even less predictable (Gilman, 1985) because less is known about their statistics, and because of a greater stochastic element in their occurrence. These two views need to be examined and reconciled in the case of Prairie droughts.

According to Pearce (1985) "Future progress in medium and longer term prediction will depend crucially on progress in understanding the dynamical and physical processes involved on these time scales....This is likely to be achieved primarily through experimentation with numerical models linked with sophisticated diagnostic studies of observational data on the global scale". This sentiment is reinforced by Preisendorfer and Mobley (1984), who "hope that future research will lead to hybrid dynamical-statistical-analog methods which will indeed be of significant importance".

Thus, numerical models are likely to play an increasing role in producing the early part of a monthly forecast, supplemented by empirical methodology beyond that. Because of this, monthly and seasonal STCP may well diverge during the next decade (Rasmusson, 1987), with dynamical methodology becoming increasingly used in monthly predictions. Seasonal forecasting, on the other hand, will likely continue to be dominated by empirical methods, but with inroads by coupled ocean-atmosphere-land surface dynamical models. Numerical modelling will also be able to provide a measure of the degree of probability or confidence to be associated with the forecast. If dynamical models are to become capable of predicting on the monthly-to-seasonal time-scale, they will have to be able to simulate faithfully the life-cycles of individual synoptic systems and their feedbacks, while simpler models must include parameterizations of transient-flux convergences to reproduce these feedbacks (Hoskins and Sardeshmukh, 1987).

Part 4. The Drought Forecast System

Drought forecasting is best considered in the context of the entire drought forecast system of which it forms part (Fig. 12). The preparation of a forecast requires input data and a forecasting methodology. After the forecast is prepared, it must be distributed, in suitable format(s), to potential users. The users, in turn, will respond to the forecast by taking appropriate actions. Continuous monitoring of regional meteorological drought conditions is indispensable for the assessment of forecast accuracy, and to provide information that may be used to develop improvements in forecasting methodology.

4.1 Who are the potential users?

While monthly and seasonal climate outlooks have been issued for a number of years by many national meteorological services, they have been used much less in decision making than the regular short- and medium-range weather forecasts (Thomas, 1979). A Canadian survey of potential users of climate forecasts, from various environmental and economic sectors (Thomas and McKay, 1978), is summarized in Table 1. The responses showed clearly the desire for climate outlooks ranging from one month to several seasons ahead, as well as a need for better access to current climate information. Although the respondents tended to view long-range forecasts with scepticism, they nevertheless wished to see the forecasts provided so that they could be tested.

Beckford et al. (1983) investigated the usefulness of climate forecasts to the Canadian Wheat Board (CWB). As the main marketing agency for western-Canadian grains, the CWB monitors crop yields and other agricultural activities in all of the major grain-growing areas of the world. Skillful predictions of drought occurrence, for these other areas as well as the Canadian Prairies, would be very useful in their operations. Their preference is for temperature and precipitation forecasts using a scale of quintiles (much below, below, normal, above, much above) or finer. Although predictions for periods as short as one month would be useful, the value of the forecast to them would increase as the length of the prediction period increased. Long-term forecasts for periods of one or two decades would also be valuable for planning purposes. They indicated that forecast accuracy would have to exceed a minimum level, and expressed the desire to receive

the forecasts on a confidential basis.

As part of the present study, a number of potential users were surveyed with respect to their needs regarding drought forecasts. As many as possible were interviewed personally, or by telephone, with the remainder being contacted by mail. The questionnaire, together with a list of the potential users contacted, and a summary of their responses may be found in Appendix B.

Almost all of the organizations that were contacted were interested in the possibility of skillful drought forecasts becoming available within the next decade. Most felt that forecasts in the one month to one season time range would be useful to them, although some preferred longer periods. Potential uses of the forecasts included:

--planning preventative measures to reduce impacts;
--aiding in decision making for new developments;
--aiding in budgeting for drought-related expenses;
--information dispersal, advice, education; and
--providing input for computer models of soil moisture, lake levels, etc.

The preferred forecast parameter was precipitation, in terms of percentiles of normal. Temperature, evapotranspiration, wind and sunshine were also desired by some users. A few expressed the wish for forecasts of a drought or crop stress index. The expression of degree of confidence in the forecast was deemed more important than expressing the forecast in terms of probabilities of occurrence. A monthly frequency of issue was preferred by most, although for some, twice a year would suffice. It was generally agreed that such a forecast would be of great value, if accurate, although not all were eager to pay directly for it.

The above "wish list" may be compared with a that from a survey carried out early in 1987 by the Canadian Climate Centre. Those surveyed were actual recipients of the experimental 30-day precipitation and temperature, and seasonal temperature, forecasts (Scholefield, 1987). About 80% of the respondents found the 30-day temperature forecasts to be useful, while fewer than half found the 30-day precipitation, and the seasonal temperature, forecasts to be of value. The survey also solicited suggestions for improvements to the forecasts. Topping the list was greater forecast accuracy. However, almost as popular were two

suggestions involving presentation format, while a small number did not like the forecasts and felt they should be discontinued.

4.2 Forecast preparation and delivery

The most critical part of the forecast system is the actual preparation of a forecast, having demonstrable skill, from the input data. The development of the methodology needed to prepare a usable forecast requires a considerable amount of research effort.

The first step in the preparation of a forecast involves the collection and management of input data (see Appendix C). This is becoming an increasingly complex task as more and more sources and types of data become available. Verifying the integrity of the data and preparing them for further use and analysis require considerable care (Jenne and Joseph, 1978; Ropelewski et al., 1985).

Various methodologies for preparing forecasts have been described and assessed in the previous chapter. However, before an actual forecast is issued a number of important questions have to be considered. The first is whether a forecast should be issued at all under certain circumstances. As long ago as 1936, G.T. Walker questioned the advisability of issuing a forecast when the degree of confidence in it was low. He felt that it was "better to admit your limitations, and only speak when you can do so with some safety than to issue predictions when they are little more than guesses". This argument is the basis for the use of forecast probabilities and confidence limits, which will be discussed later in this section.

With regard to its acceptance by the user, the actual presentation of the forecast may be almost as important as its accuracy. Three important aspects of presentation are: timing, format, and delivery method. Easterling and Mjelde (1987) found that many subscribers were just as concerned with forecast lead time (time between forecast release and beginning of prediction period) as they were with forecast accuracy. A survey of U.S. agribusiness (Lamb et al., 1985) found that many respondents would consider to be useful: a prediction of the general character of the coming summer, if issued before mid-April; and a prediction of autumn conditions, if issued with several months lead time

(agricultural sector).

A Canadian Wheat Board Survey (Beckford et al., 1983), indicated that forecasts for the following month would have value, but that the value would increase for prediction periods up to a year or more. While their main concern would be the wheat growing season, they would also be interested in conditions during the balance of the year, because of effects on grain drying, storage and transportation, and on soil moisture at planting time.

The user survey in the present study (see Appendix B) revealed that the majority would prefer monthly forecasts, while a few indicated that seasonal or semi-annual (spring and fall) forecasts would be more desirable.

The delivery system should include a facility for the issuance of special "climate warnings" or "drought alerts", when appropriate. These warnings would be supplementary to the regular forecasts, and should be given wide distribution, and flagged to attract the user's attention.

The present STCP format used by the Canadian Climate Centre, which is based on a careful assessment of current forecast accuracy, (Fig. 13a) involves only temperature, using but two classes (above and below normal). The presentation used by the Climate Analysis Center of the U.S. National Oceanic and Atmospheric Administration (Fig. 13b) expresses the expected precipitation and temperature anomalies in terms of probabilities of being above or below normal. Another way of assessing forecast probability is the "Model Output Statistics" method of Glahn and Lowry (1972). This being used to produce precipitation probability forecasts for major Australian cities, and the superior skill and usefulness of these forecasts have been reported by Tapp et al. (1986).

An alternative method of expressing forecast uncertainty is by attaching a confidence value to each forecast. This method is used for the STCPs produced by the United Kingdom Meteorological Office (Fig. 14), with the letters A to E forming a scale of decreasing confidence, based on a subjective assessment of the consistency of forecast indications. Since the system has been in operation, no forecasts have been issued with the highest rating (A) and only 1 percent of the forecasts have received a B rating. Twenty percent have received a C rating, while the remaining

79 percent were given D and E ratings (Jones, 1987). Forecast verification has shown those forecasts issued with a C rating to be skillful, while those issued with D and E ratings were not. A more objective method of assessing probable forecast errors, at least for numerical forecasts, is the "stochastic-dynamic" method described by Thompson (1985). Such assessment might be used as the basis for a confidence rating system.

The survey of Lamb et al. (1985) showed that many potential users of climate predictions considered them to be presented in an inappropriate fashion for their use. This indicates the need to perform research into format design, which may well indicate the need for several formats for different user groups. While temperature and precipitation forecasts may suit some users, others may find a particular drought index more useful. It may be necessary for the issuing agency to provide a number of output formats initially until the users decide which ones they prefer.

Spatial resolution is a consideration of many potential users (Lamb and Sonka, 1985). At present, the spatial resolution of most STCPs is relatively coarse (Fig. 13), but this is likely to improve as more skillful and accurate forecasts become realizable.

The user survey (see Appendix B) indicated that some were satisfied with the usual temperature and precipitation format of existing long-range forecasts products. Others wished for a specific drought forecast specifying expected times of initiation and termination of the drought, together with some indication of its severity. Some would be happy with precipitation predictions as percentiles of normal, while others expressed a preference for conversion to drought indices, or soil moisture or water availability. Many would prefer the forecast expressed in terms of probability of occurrence, or degree of confidence.

There is a wide spectrum of possibilities for the delivery of drought forecasts. They may range from the regular STCPs issued through the news media to the general public (Finger et al., 1985) to individualized forecasts, issued to subscribers on a confidential basis (Beckford et al., 1983). The survey of Lamb et al. (1985) emphasized the importance of having a delivery system that is appropriate to the requirements of the user or subscriber. Thus, it may be necessary to tailor not only the forecast format and timing, but also the method of

delivery, to the individual needs of users and subscribers. While the postal service may be quite adequate for the delivery of longer-range forecasts, and those having a long lead time, shorter-range forecasts and those with zero lead time may require an electronic delivery system (Hubbard, 1987).

A description of a number of available climate information products, including STCPs, may be found in Appendix C.

4.3 Forecast verification

Forecast verification is an important element of any long-range forecast program, not only in regard to its role in research and the development of improved forecast methodology, but also to provide information for prospective users, and assistance in improving the delivery system.

A survey of existing verification methods was carried out by Dobryshman (1972). More recently, Jolliffe and Foord (1975) used a contingency table to calculate a "measure of association" between predicted and observed climatic variables. This measure of association has a value of zero for random forecasts, +1 for perfectly correct forecasts, and -1 for perfectly incorrect forecasts. Tapp (1986) proposed a novel measure of forecast accuracy, based on the removal of persistence. His measure (m) would be defined as the ratio of the excess of actual accuracy (F) over persistence (P) to the total possible, i.e.

$$m = (F - P) / (T - P)$$

where T is the total. While this is an unduly-harsh measure when compared with existing scales, it (or some other) generally-accepted method is needed to eliminate the confusion of the many existing methods of comparison. Murphy and Winkler (1987) suggested that a diagnostic approach to forecast verification "might provide the basis for a more effective verification system from the viewpoints of both the producers and users of the forecasts", as well as serve to identify ways in which the forecasts might be improved.

4.4 Drought monitoring

Real-time assessment of meteorological drought requires the collection of precipitation and/or other data describing

moisture conditions over the area of interest. Surface-based measurements (reviewed by Hubbard, 1987) are rapidly giving way to satellite remote-sensed measurements (described by Tucker and Goward, 1987). The latter have to be calibrated using surface measurements, but can provide much better spatial resolution with less effort.

The purpose of drought monitoring is to detect the presence of drought, as early as possible in its occurrence, and to assess its spatial extent and severity. Indicators of drought vary from those based on precipitation deficiency alone (e.g. Katz and Glantz, 1986; Janowiak et al., 1986) to complex models of soil moisture and hydrologic systems. Laycock (1960) used precipitation data together with the Thornthwaite estimate of potential evapotranspiration to calculate moisture deficits for the years 1921-1950 in the three Prairie Provinces. More recently, soil moisture was brought into the picture through the use of such models as the Versatile Soil Moisture Budget (Dyer and Mack, 1984). Similar procedures are used operationally in Agriculture Canada's Soil Moisture Estimator Program, and the Canadian Climate Centre's Climatic Perspectives (Johnstone and Louie, 1984).

A drought-warning system for spring forage in western Canada (FoDEWS), using the Versatile Budget, was developed by Dyer et al. (1982). The model predicts likely soil moisture conditions using a combination of actual precipitation and temperature data for the current year and historical data. As new data come in, they are entered into the model and the prediction is updated. Similar "climatic water budget" methods were described by Johnstone and Louie (1984), and used by Street and McNichol (1983) and the AES Drought Study Group (1986) to analyze drought occurrence on the Prairies during the past half century.

Two of the most widely-used drought indicators are the Palmer Drought Index (Palmer, 1965) and the Crop Moisture Index (Palmer, 1968). The PDI tends to reflect the moisture stress experienced by deep rooted crops, as well as changes in water levels of ponds and lakes (Strommen, 1984; Jones, 1984), while the CMI is a more useful indicator of the moisture conditions of shallow-rooted crops (Jones, 1987). The two indices complement each other as useful regional drought-monitoring tools (Felch, 1978). Oladipo (1985) compared the PDI with two other precipitation-based drought indices. He concluded that each was effective in detecting meteorological drought, and

that precipitation was the most important climatic factor affecting agricultural drought. Recently, Janowiak et al. (1986) developed an objective technique for monitoring regional precipitation deficits on time scales of a month or longer. They found that their technique compared favourably with the PDI and CMI approaches.

The main remote-sensing approach to drought monitoring is based on changes in leaf area and in the amount of photosynthetic pigment in green plants as they respond to drought stress (Wiegand et al., 1983). These changes can be detected remotely through variations in the spectral reflectivity of a vegetated surface, using NOAA's advanced very high resolution radiometer (AVHRR). Walsh (1987b) compared NOAA AVHRR measurements with the CMI for four summer periods in Oklahoma and, using multiple regression analysis, was able to explain 80% of the variance in the data. Other remote-sensing methods, using synthetic-aperture radar and scatterometer sensors for example, will also likely find use in monitoring soil moisture (Schmugge, 1978; McQuillan, 1986; Wetzel and Woodward, 1987). Epp and Polson (1987) compared AVHRR and Landsat multi-spectral scanning data with crop-yields, as a means of studying the spatial variability of the 1984/85 drought in Saskatchewan.

A number of organizations interested in monitoring drought conditions already exist on the Prairies. The PFRA itself was formed specifically to deal with drought and since its inception has developed many strategies to monitor, and mitigate, drought and its consequences. In Alberta, a Drought Monitoring Committee was formed in 1984 to assess precipitation, soil moisture, crop and pasture conditions, and surface and underground water supplies (O'Brien, 1986). A similar committee took shape in Manitoba during the past year.

4.5 Forecast user response

The ultimate purpose in forecasting drought is to provide society with sufficient warning of its occurrence for some mitigating action to be taken. This requires that possibilities for responsive actions exist, and that a plan for implementing these actions be in place before the need to use them arises.

Droughts vary in their magnitude, frequency and duration of occurrence, as well as in their spatial characteristics

(Yevjevich et al., 1978). They have their earliest effects on soil moisture and vegetative cover, resulting in crop losses and wind erosion. Next to be affected are stream flows and lake levels, resulting in reduced availability of water for recreation, irrigation and hydroelectric power generation. If a drought continues, ground water supplies may be diminished, and even species composition of natural lands affected (Abouguendia and Coupland, 1985). Ultimately, the drought effects permeate all parts of the biosphere and the socio-economic system (Wilhite and Glantz, 1987).

The drought of the 1930s struck the Prairies after the experience ofa relatively wet period in the 1920s (Ripley, 1986). The disastrous impacts of the sequence of dry years in the 30s were exacerbated because many of those farming at the time had little idea how to deal with them. During the ensuing years, with the help of the PFRA, the establishment of many dryland management practices (Hill, 1979; LeRoux, 1984) has considerably reduced the sensitivity of Prairie agriculture to drought. Although the threat has been lessened, it has not been removed. Recent studies by Warrick (1984), Arthur and Kraft (1986), and Williams et al. (1987) found that in spite of technological improvements the agricultural system would still suffer great losses if the 1930's drought were repeated.

In most parts of the world, agricultural operations are still largely dependent on rainfall and suffer severely when it fails to arrive. The modelling approach is being used increasingly to predict the impacts of climate variations, such as drought, on agriculture and the food system. The main problems associated with such an exercise (Liverman, 1987) relate to the integration of sub-models, such as those dealing with climate, crop-growth and economics.

Not long after the agricultural system feels the effects of a drought, water supplies begin to be affected. Although Prairie society has "generally adjusted to withstand the normal range of fluctuations.....serious losses can and have resulted during prolonged dry spells" (Davis, 1984). A mild, dry winter in 1976-77 led to severe water-supply problems over much of the Prairies the following summer (Allsopp and Richardson, 1977; McKay, 1980). This had major impacts on water use for irrigation, power generation and domestic purposes (Davis, 1984). Subsequent droughts in 1980 and 1981 caused water tables to drop low enough to affect shallow farm and community wells, as well as ferry transportation on some Prairie rivers.

The Prairie drought of 1984-85 came on the heels of dry conditions the previous year (Hopkinson, 1984). It affected agricultural production over most of the southern Prairies, and resulted in an estimated loss of over a billion dollars in Gross Domestic Product (Fautley et al., 1986). The effects were aggravated by low crop prices and high input prices and led to reductions in farm implement sales and construction starts, political controversy, and general pessimism (O'Brien, 1986).

Gilman (1985) stressed the necessity for economic work to be done as a background to the use of a climate forecast. The required work is to determine what the critical values of their systems are, what the climatic effects on those systems will be, and what strategies are available to deal with them. If that work is not done, there is little likelihood of the subscriber getting a useful result out of the forecast. A study by Glantz (1979), following the 1974 Prairie drought, posed the question "what would the impacts of the drought have been if agricultural decision makers had been warned about it the preceding autumn?". While some respondents felt that such a forecast might have brought them benefits, others considered that they had no alternative than to do what they did anyway. The study indicates that the production of even a highly-skillful drought forecast may not, by itself, lead to socio-economic benefits.

An adequate drought policy and proper planning decisions can certainly help reduce the negative effects of drought (Woo, 1982; Wilhite, 1987; Wilhite and Easterling, 1987), as can timely government response to drought situations (Hecht, 1983; Wilhite, 1983; Wilhite et al., 1986). However, what happens when government advice is incorrect? A study by Glantz (1982) addressed the possible liability of an agency for issuing an incorrect forecast of drought. The U.S. Bureau of Reclamation predicted a shortage of irrigation water for the Yakima Valley of Washington, and instituted a rationing program. The prediction proved to be erroneous, and many farmers took legal action against the Bureau to recover losses. The study "raises the issue of who, if anyone, should bear the responsibility for the societal implications of such forecasts" (Glantz, 1982).

One common characteristic of droughts is the difficulty of recognizing them before they are well advanced. Once a drought is recognized, however, the important question becomes "When

will it end?". Predicting the end of a drought is probably no easier, or more difficult, than predicting the beginning, and similar forecasting methods can be used. Karl et al. (1987) described an approach to specifying the climatological probability of drought termination, using the Palmer Drought Index. Its usefulness as an aid in drought mitigation activities was demonstrated by applying it to the continental U.S.

On a more positive note, we should consider what can be done to ameliorate, or mitigate, a drought while it is occurring. It is possible that a number of mitigation measures would likely be of value (Supalla, 1984; Rosenberg, 1980; Nicholaichuk and Gray, 1986; Banga et al., 1986). These include: greater use of snow management practices, improved irrigation management, selection of crop cultivars for drought tolerance, development of tillage practices for soil water conservation and greater use of windbreaks. With reference to the Canadian Prairies, McKay (1980) recommended that more effective use be made of meteorological information by analyzing statistically the meteorological characteristics of historical droughts and their social, economic and environmental consequences. This knowledge should then be exploited for the enhancement of the mitigation measures mentioned above and for the development of strategic and tactical plans for drought mitigation.

Another potential drought mitigation weapon is cloud seeding. Although not yet very successful for precipitation enhancement from mid-latitude convective clouds (World Meteorological Organization, 1982a), it is possible that the method will become more effective in the future. A important question regarding its use to mitigate drought is whether there is a greater or lesser chance of success during drought compared with non-drought periods. Flynn and Griffiths (1980) analyzed rainfall during severe drought and non-drought periods in Texas. They found that severe droughts were characterized by both fewer and less intense rain events than normal. Although that meant fewer potential seeding days, there nevertheless was a possibility of limited success on those days. Data supplied by Isaac (1987) indicates that for some drought periods (on the Canadian Prairies), suitable clouds for seeding can exist in amounts comparable to the 30-year average amount. Thus the outlook for cloud-seeding during drought periods may not be as gloomy as conventional wisdom might indicate. An aspect that merits further investigation concerns

the availability of naturally-occurring freezing nuclei during periods of drought. Many of these nuclei are produced by decomposition of plant material and are carried into the atmosphere by convection currents. While total suspended particle amounts may not be significantly different from normal during some drought periods (LaDochy and Annett, 1982), it is possible that the freezing nuclei proportion may differ.

Parry and Carter (1987) concluded that although the "connections between a climatic event, its biophysical effects, the economic costs of prevention or compensation, and the social impacts of all of these are imperfectly understood", there has been "some degree of success in simulating these connections with a hierarchy of models of varying degrees of complexity". This feeling was echoed by Lamb (1987), who suggested that "a truly inter-disciplinary, as opposed to multi-disciplinary, effort will thus be required".

Part 5. Major Conclusions and Recommendations

5.1 General drought research needs

The ultimate aim of most climate programs is the "minimization of the adverse socio-economic consequences of climatic variability" (Lamb, 1981). To achieve this end with respect to drought, effort is needed to improve all components of the forecast system (Fig. 12) from data collection, through forecast preparation and distribution, to user response and forecast assessment. At the same time as we attempt to do this, we should keep in mind that we are dealing with a system composed of many interactions, and that changes to one component will likely affect others.

The first need is for better observational data (Namias, 1981b; Rasmusson, 1987), not only for the atmosphere but also for temperature and currents in the upper ocean. Almost as important are more accurate data describing land surface boundary conditions. There is still room for improving the flow of routine meteorological data between countries, and developing better techniques for its analysis (Pontificiae Academiae Scientiarum, 1987). Nevertheless, great strides have been made in recent years in making historical and current meteorological datasets more readily available to the scientific community (Gilman, 1985). These are being used for both research and operational purposes. Similar advancements have also been made in the development of remote-sensing methods to replace and supplement surface-based observations. It is likely that the latter network will not improve much in the future, if at all. Thus, more reliance will have to be placed on remote-sensed data, and on getting the most out of the surface-based data that are available. The work of Lovejoy et al. (1986) dealing with sparse measurement networks may help. In their words--"techniques of multi (fractal)-dimensional analysis and simulation may ultimately help clarify basic problems in predictability. In the short term, we may expect rapid development of statistical techniques to provide important corrections to data lacking in dimensional resolution. Improved forecasts over a wide range of timescales could be possible".

Under the guidance of the World Climate Programme, the global climate system is now being studied by a large number of modellers, theoreticians, diagnosticians, and experimentalists (Gilman, 1985). The availability of more powerful computing

hardware will encourage further improvements in climate modelling, which will likely focus on surface boundary processes and oceanic circulation. Theoretical work in both meteorology and oceanography will help improve our understanding of the climate system, and provide better tools for the modellers. Diagnosticians will continue to uncover secrets about the system, that are hidden in the vast files of current and historical data. New diagnostic approaches, both subjective and objective, will likely be developed. Possible examples include examination of satellite images of the movement of weather systems. A series of films by Fox (1978) show the movement of weather systems over the eastern North Pacific Ocean during several seasons. Anomalies in these motions have been related to subsequent weather over western North America. Another approach, described by Lewis (1987), uses time-lapse weather video to animate series of maps of precipitation, temperature, snow cover, pressure, etc. This presentation also may assist in the subjective recognition of patterns, that might otherwise go unnoticed. Some techniques of multivariate analysis that will likely be more fully exploited in the future are canonical correlation analysis (Nicholls, 1987; Barnett and Preisendorfer, 1987), entropy minimax (Christensen and Eilbert, 1985), and map-pattern correlation (Blasing, 1979). Experimentalists need to develop new experimental design methodologies for the testing and verification of dynamic models, if meaningful inference is to be drawn from them (Pontificiae Academiae Scientiarum, 1987). Finally, continuing media support and public interest will be necessary if the above activities are to receive adequate funding.

In the future, there will be a need for all of the above approaches to be used in an integrated manner by meteorologists, oceanographers, and cryospheric and soil scientists. More attention will have to be focussed on surface boundary processes, particularly air-sea interactions. Given a fertile research environment and well-trained and enthusiastic workers, Namias (1981b) believes that long-range forecasts, up to a year ahead, are within reach. He predicts that future forecast methodology will combine statistical, synoptic, and physical features. How the various approaches will be blended into the final product is, perhaps, "one of the most fundamental problems awaiting the climate forecaster" (Barnett and Somerville, 1983).

A largely-neglected area of STCP has been the interfacing of the forecast with the users. If a need for such predictions exists, and many surveys indicate that it does, then great care must be taken to package the product properly and to direct it where it will do the most good. The specification of the forecaster's confidence in the prediction is imperative (Gilman, 1986). While some forecasting procedures, such as analogue and simple statistical techniques, are conducive to providing confidence measures, others, such as statistical-physical and dynamical-numerical, are not (Barnett and Somerville, 1983). When forecast confidence is very low, it may be better to issue no forecast, or at least flag the forecast as being uncertain, rather than to risk losing user credibility. An approach that would improve communication of the forecaster's ideas to the user would be the use of climate scenarios, instead of the usual type of forecasts (Lamb, 1987). These internally-consistent scenarios would be based on all the information available to the forecaster, and would show the range of conditions that could plausibly occur. Climatic predictions would then be in the form of a group of scenarios having assigned relative probabilities.

It is necessary to determine which segments of society are able to take advantage of skillful climate forecasts (Lamb, 1981). This will identify the regions, weather parameters, and time periods that climate forecasts ought to focus on, in order to maximize benefits. Users must have other options open to them, and must have planned mitigative action in advance in order to utilize a drought forecast properly (Yevjevich et al., 1983). This points to the need for further research into the development of methods to avoid and reduce drought impacts on all segments of society (Yevjevich et al., 1978).

The following are key areas of drought research needs (Wilhite et al, 1987):

--drought prediction;
--drought detection, monitoring, and early warning;
--drought impact assessment;
--drought adaptation and adjustment;
--drought planning and response.

Warrick (1975) proposed that the following further investment be put into the prediction and forecasting aspect of drought research in the United States over a period of 5 to 10 years:

--climate modelling, 200 person-years (p-y);
--drought probability studies, 100 p-y; and

--use of information, 70 p-y.

On a relative population basis, a Canadian investment of about one-tenth of the above might be appropriate.

5.2 Drought research needs on the Prairies

Data

Relatively few studies have been carried out of either the genetic or empiric characteristics of drought on the Canadian Prairies. At least part of the reason is the scarcity of observing stations, particularly upper-air stations, over much of the region. Connected with this is the relatively short period of record at most observing stations. One need, then, is to assess the adequacy of the present observing network, in relation to the requirements for drought research, as well as drought monitoring, and if necessary, press for improvements in the future. Greater use of satellite data, and the fractal dimensional-analysis approach of Lovejoy et al. (1986), should both be considered.

The existing methods of drought monitoring need to be assessed in order to determine which are the most appropriate to the needs of the Canadian Prairies. The PDI and CMI, in spite of their limitations, are widely used and understood. On the other hand, satellite monitoring gives a more complete spatial view, and relies less heavily on surface observational data. A combination of the objective precipitation-anomaly classification of Janowiak et al. (1986) with satellite-monitoring data (Hougham, 1987) offers the greatest promise for the Prairies.

Drought patterns

Considerably more analysis of the spatial and temporal patterns of drought on the Prairies is needed, from both the genetic and empiric approaches. This is justified now that longer and more reliable data sets are becoming available, along with more powerful methods of statistical analysis. On the other hand, the long-term variability of climate cannot be ignored. The climate of the coming decades may well be different from that of the past, because of natural as well as anthropogenic factors. In addition, our perception of climate may well change as observational methodology evolves from surface-based point data to a greater reliance on remote-sensed data. Both of the above are likely to lead to the

greater use of numerical modelling techniques in drought-pattern analysis.

The pioneering genetic studies of Borchert (1950), Villmow (1956), and Bryson (1966) need to be continued and expanded. Synoptic-type catalogues, such as those of Augulis (1969), Rasch and MacDonald (1975) and Barry et al. (1981) are useful for developing and testing hypotheses, and may also be used operationally in a specification role, i.e. to interpret forecasts of upper-level flow patterns in terms of surface probabilities of precipitation. Only a few such studies have been carried out for the Prairies (Dey and Chakravarti, 1976; Amsden, 1985; Knox and Lawford, 1988).

Empiric studies have been far more numerous, looking mainly at patterns of precipitation (Connor, 1933; Richman and Lamb, 1987), drought indices (Karl, 1983; Oladipo, 1986 and 1987), and soil moisture (Laycock, 1960; Street and Findlay, 1981). Some of these studies (e.g. Oladipo, 1987) have attempted to find statistical links between observed patterns and potential forcing functions such as the QBO and ENSO. That of Walsh et al. (1982) used factor analysis to identify synoptic-scale regions in the U.S. for which monthly precipitation amounts showed the greatest coherence. The patterns identified were consistent with known cyclone trajectories, and displayed seasonal continuity except in summer, when convective precipitation results in minimum of spatial coherence. Richman and Lamb (1987) used several eigenvectorial methods to analyze spatial patterns of three and seven-day summer precipitation in southern Canada. They identified five coherent regions for the Prairies (Fig. 2) that they felt would be useful for crop-yield modelling, STCP, and climatic change research. Recently, Lozowski (1988) has examined monthly-mean temperature time series using a chaos-theory approach. Although the method may not have direct forecasting potential, it may help in understanding some of the observed variations in the climatic elements.

Hypotheses

Hypotheses regarding the causes of Prairie drought need to be developed and tested. There are two methods of doing this--by analyzing historical data, and through numerical model simulations. Both methods should be exploited. Historical data, and the data from many model simulation runs are available for analysis at the Canadian Climate Centre, the

Climate Analysis Center, and elsewhere. The main questions that need to be addressed are:

To what extent are Prairie droughts dependent on:

a. **internal atmospheric dynamics** --this produces stochastic variations on the time-scales involved in STCP, and is essentially unpredictable.

b. **local boundary forcing** --is changing land-use on the Prairies affecting drought characteristics? The effects of the regional boundary conditions are likely to be difficult to separate from other forcing effects because of climatic noise. While there may well be modulating effects on drought, these would be difficult to incorporate into a forecasting procedure.

c. **remote boundary forcing** --mainly El Niño, but other anomalies of SST, snow cover, etc. are also likely to be important (Walsh, 1982). This is the most promising area for STCP research. Major variations in surface conditions are now known to produce circulation anomalies, including those that are related to drought. These should be studied by: identifying the relevant boundary anomalies, and the circulation anomalies they produce; establishing their connection with Prairie drought patterns; identifying precursors of these persistent anomalies and the lag times between them and their teleconnections.

d. **external forcing** --solar cycles, volcanic eruptions, greenhouse gases, etc. While these effects remain tenuous, at least on the one to three month time scale, they may have to be taken into account if their validity can be established. It is yet to be established whether recent trends in temperature and precipitation on the Prairies (the 1980s so far have been the warmest and driest decade at Saskatoon since records began) are climatic noise or the result of external forcing.

5.3 Research recommendations for the HRD

The following are recommendations for research that should be supported by the Hydrometeorological Research Division. They relate to the analysis of temporal and spatial drought patterns on the Prairies, and the relationships between these

patterns and external forcings. Such studies may be carried out through the examination of historical data sets, as well as through the use of numerical simulations at the Canadian Climate Centre, or other centres in the U.S. and abroad. The most promising avenues for co-operative research of this type outside of Canada are likely to be the Goddard Space Flight Center (NASA), the Climate Analysis Center (NOAA), the National Center for Atmospheric Research, the Illinois State Water Survey and Scripps Institution of Oceanography.

The following identified areas of research are grouped into major and minor categories. Those listed as <u>major</u> relate closely to one another and should be considered as parts of a single package. Under the <u>secondary</u> classification are a number of other recommended research areas which may be dealt with individually.

MAJOR RECOMMENDATIONS

1. The spatial and temporal patterns of drought occurrence on the Prairies, particularly the delineation of coherent regions, should be established. More information is needed regarding the timing, duration, intensity, spatial extent, and predictability of Prairie droughts.

2. These drought patterns need to be related to synoptic situations or map-types, and in particular to up-stream and down-stream teleconnections. Relationships can then be sought between the synoptic patterns and forcing functions such as ENSO. A prime example is the PNA pattern, which is known to be associated with both ENSO and anomalous weather over western North America.

3. The associations between these synoptic situations and surface-boundary forcings such as ENSO need to be investigated. Although an ENSO signal has been recognized in the winter-time temperature field in western Canada, none has been found in the precipitation field, or in other seasons. Further investigations should be carried out, looking at cold as well as warm ENSO events. Even if the signal is present only during the winter, there may well be some carry over into the following spring and summer through soil temperature and snow cover effects.

   ENSO effects are likely to be greater over the Rocky Mountains than farther east (Cayan, 1987). This region merits study since it is the source of much of the early-summer stream flow in the Prairies.

   The effects of other local and remote surface anomalies should be investigated, using both studies of historical data sets and numerical simulations. The most promising are likely to be North Pacific Ocean SSTs, Arctic sea-ice extent, and North American snow cover and soil moisture. Several new data sets have recently become available that will assist in this. There is a major need for improving the modelling of land-surface processes to facilitate the numerical simulation side of this work.

SECONDARY RECOMMENDATIONS

1. Investigate whether droughts which are extreme, in terms of intensity, area affected, or duration, are more or less predictable than less-extreme droughts.

2. Investigate sunspot/QBO relationships with Prairie droughts, in light of the recently-discovered relationship between the QBO and the solar cycle.

3. Investigate the simplified-dynamics modelling approach to monthly and seasonal climate prediction on the Prairies.

4. Investigate potential relationships between the latitudinal distribution of atmospheric aerosols and weather patterns over the Prairies.

5. Investigate the optimum format and delivery method for supplying the drought forecast to potential users. User acceptance, comprehension and confidence should all be considered.

6. Investigate the use of indicators other than precipitation and temperature quantiles for use in drought forecasting. The various existing drought indices, such as the PDI and CMI, need further assessment and, perhaps, modification. Use of other aspects of precipitation (such as rain days, dry days and rainfall intensity) should also be considered.

7. Investigate temporal patterns in drought occurrence using a chaos-theory approach.

The above research should be conducted with as much co-operation and support of the potential users as possible. This will not only ensure that the research stays "on track", with respect to their needs, but also will help to build up credibility in the procedure by keeping them informed and involved as the work progresses.

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Table 1 -- Climate forecast and outlook periods required by various activities in Canada (from Thomas, 1979).

Field of Activity	Forecast Period	Activities
Agriculture	1-18 months	harvesting/planting
Construction	1-3 months	planning work schedules
Energy	1-3 months	heating/air conditioning
Fisheries	1-6 months	fish population prediction
Forestry	seasonal	pest and disease prediction
Land Resources	--	--
Tourism/Recreation	seasonal	planning recreation activities
Transportation	1-3 months (winter)	dealing with snow and ice
Water Resources	1-6 months	water supply/flood prediction

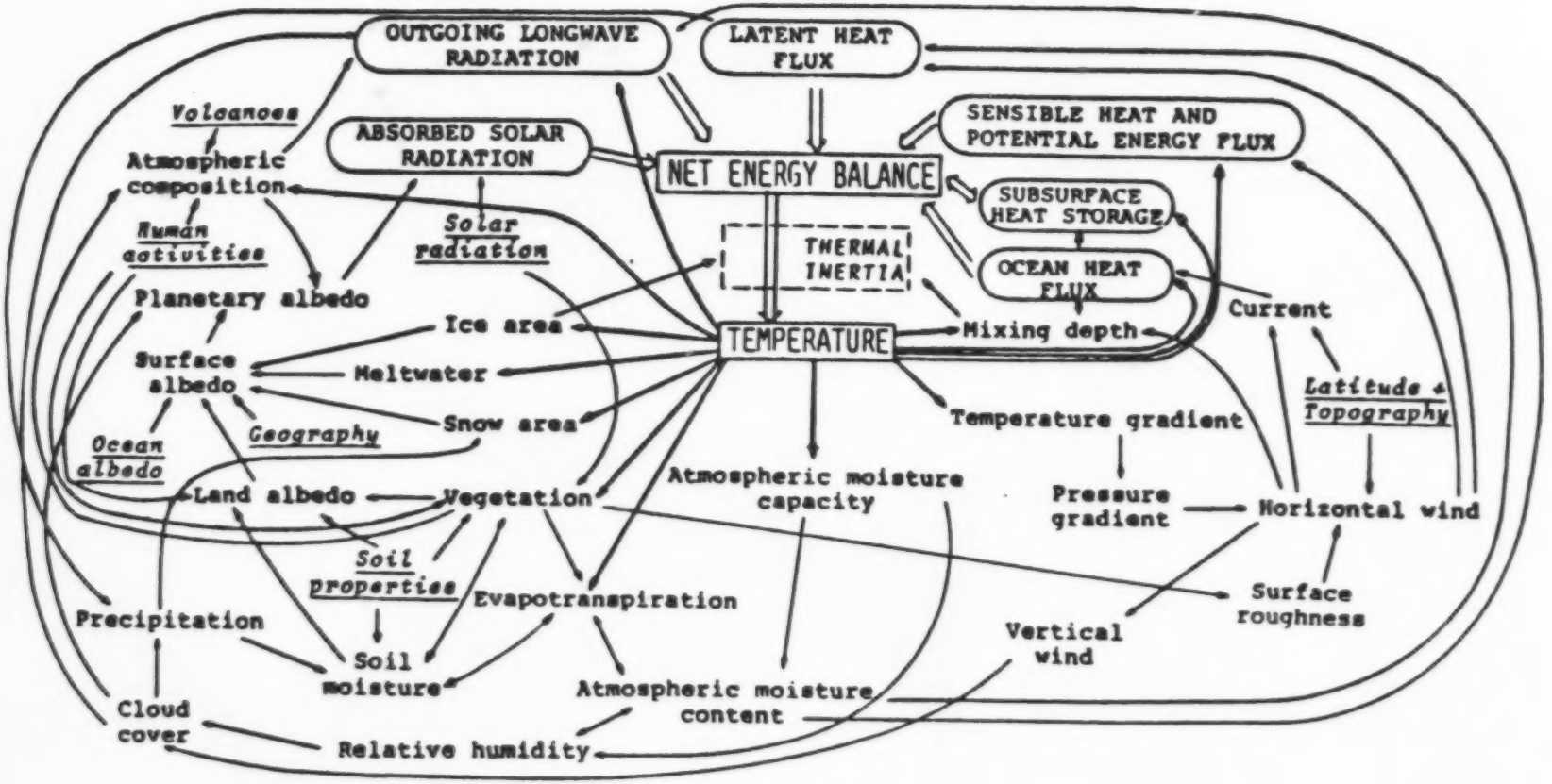


Figure 1. Climate feedback diagram (Robock, 1985).

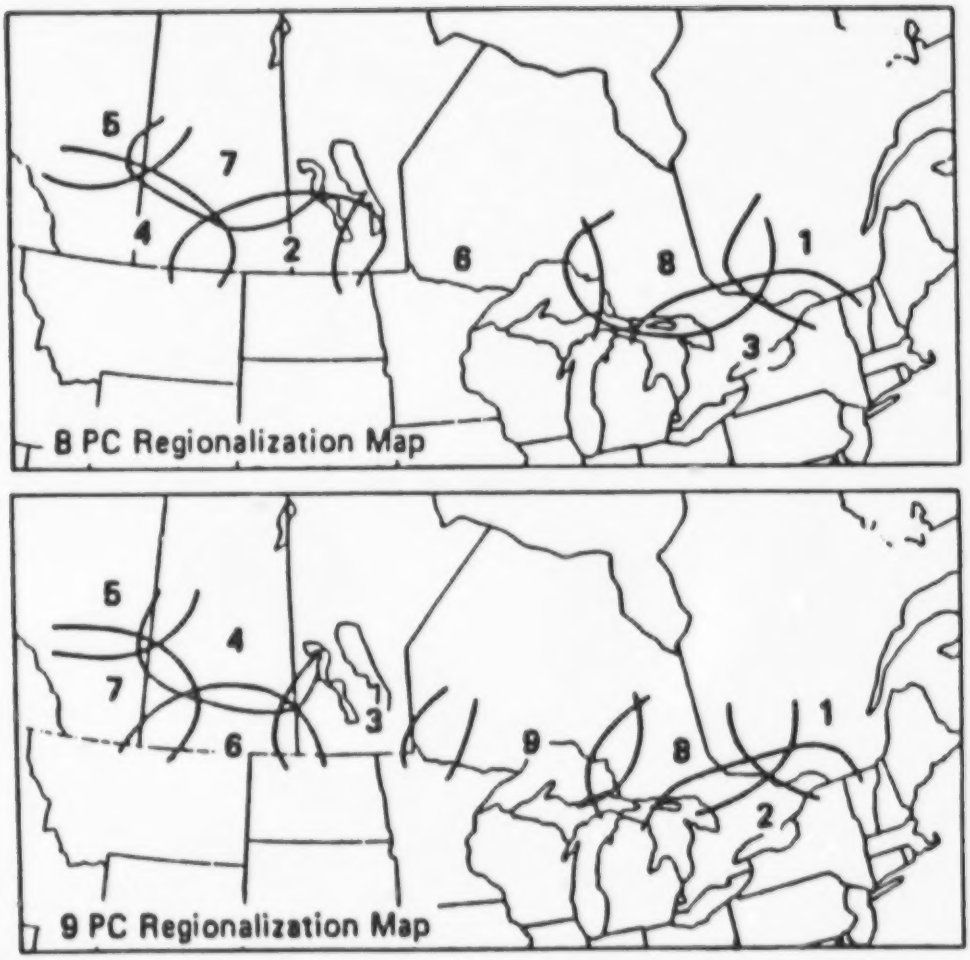
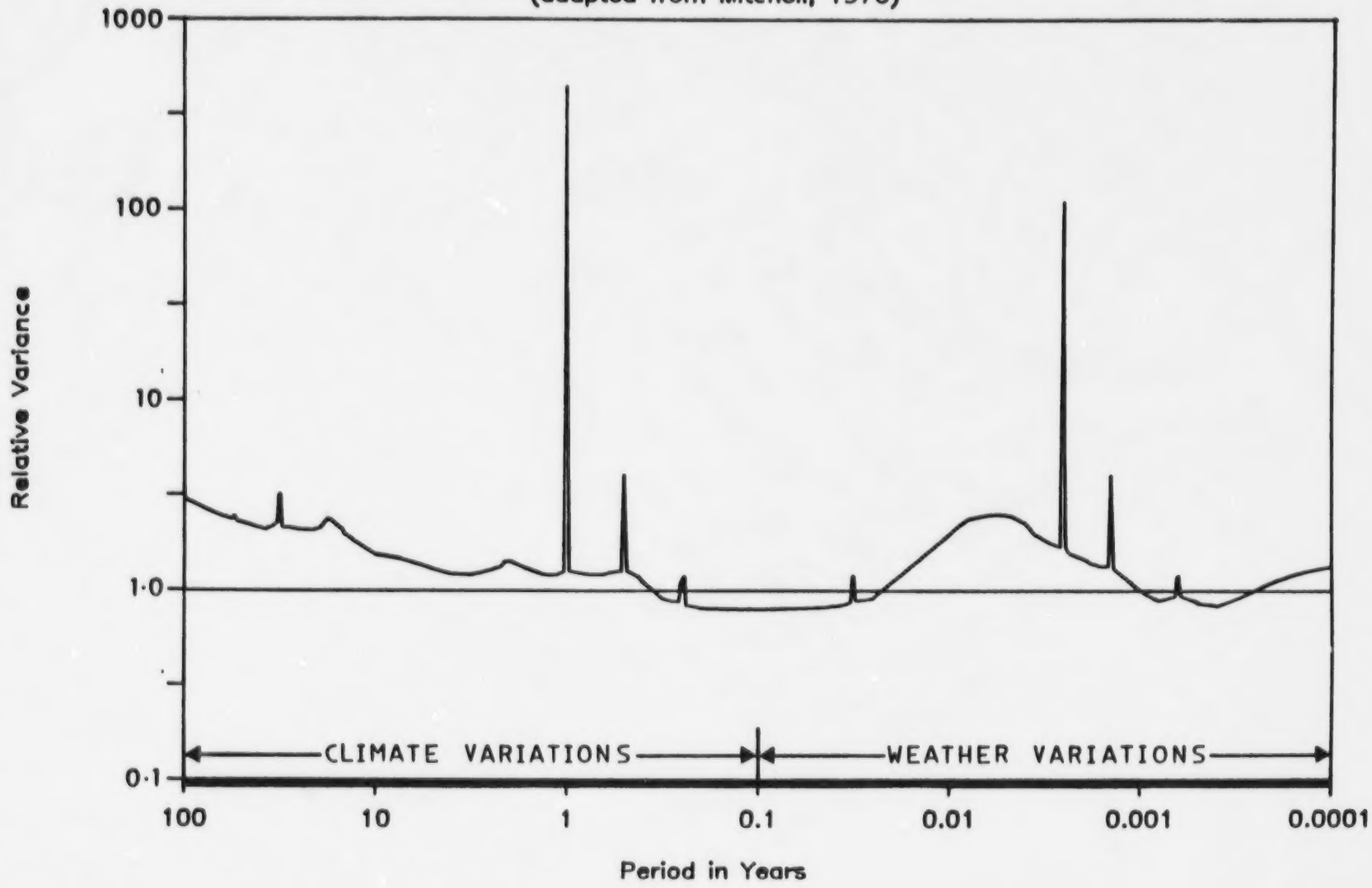


Figure 2. Growing season precipitation regions of southern Canada, selected using the Varimax-rotation of 8-9 principal components (from Richman and Lamb, 1987).

Fig. 3. Spectrum of Climate Variations.

(adapted from Mitchell, 1976)



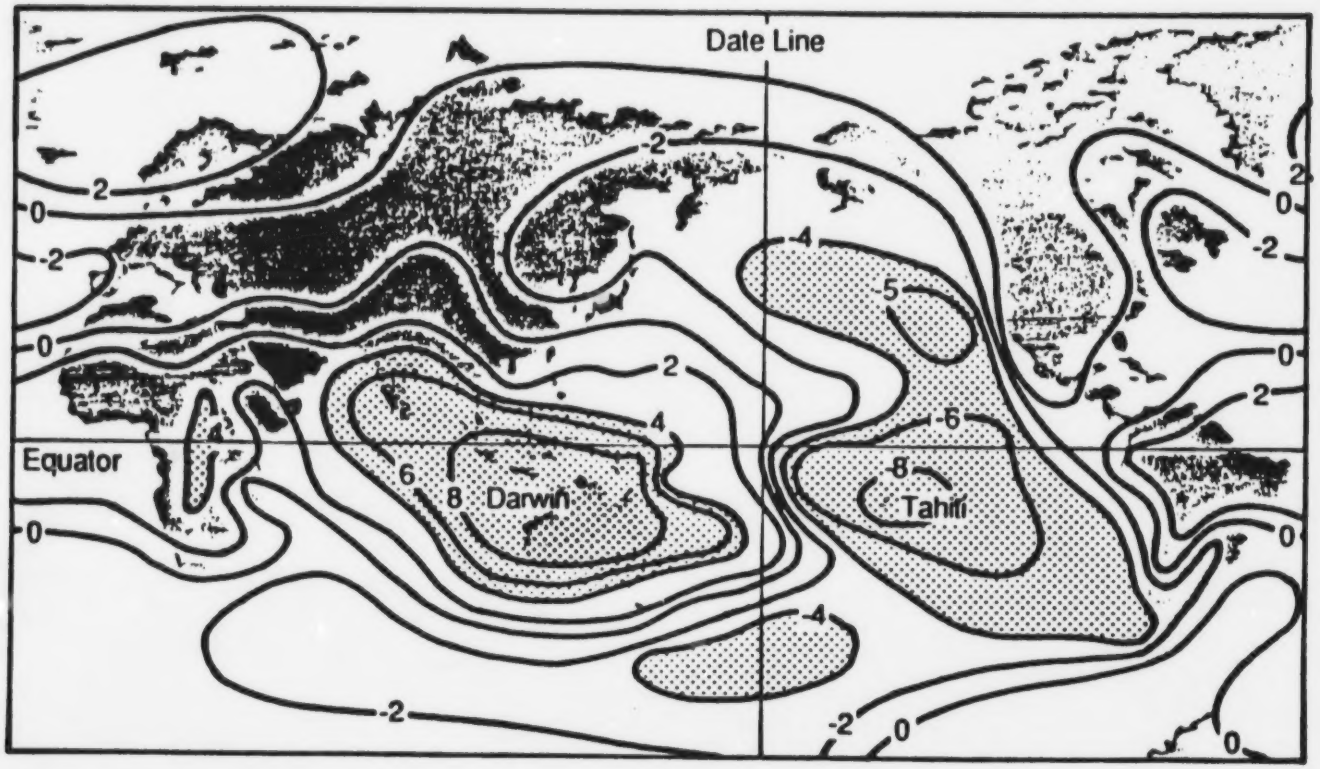


Figure 4. **Annual mean SLP correlations, illustrating the Southern Oscillation see-saw (Glantz et al, 1987).**

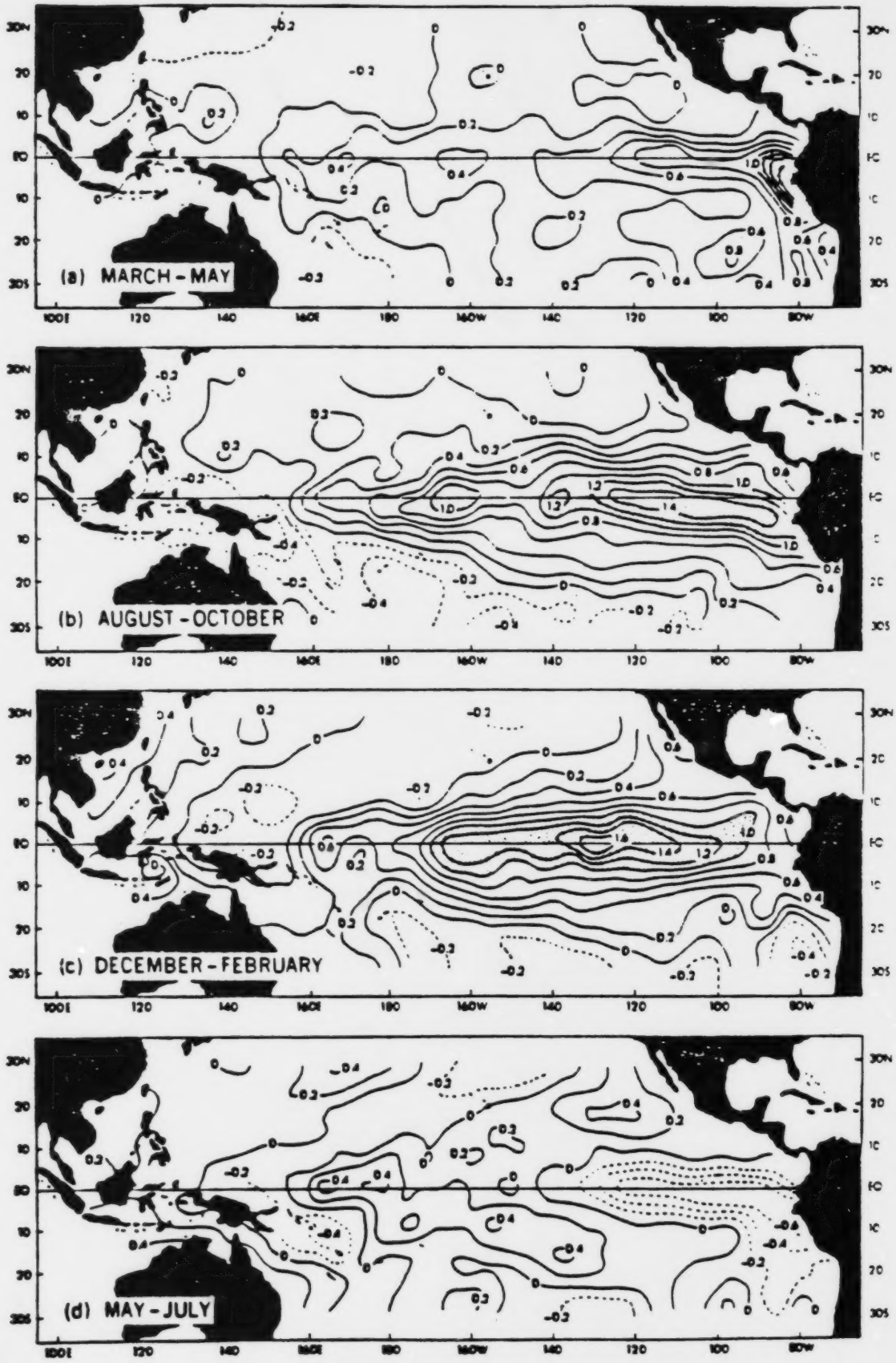


Figure 5. **Evolution of SST anomalies during a typical El Niño warm event (Philander, 1982).**

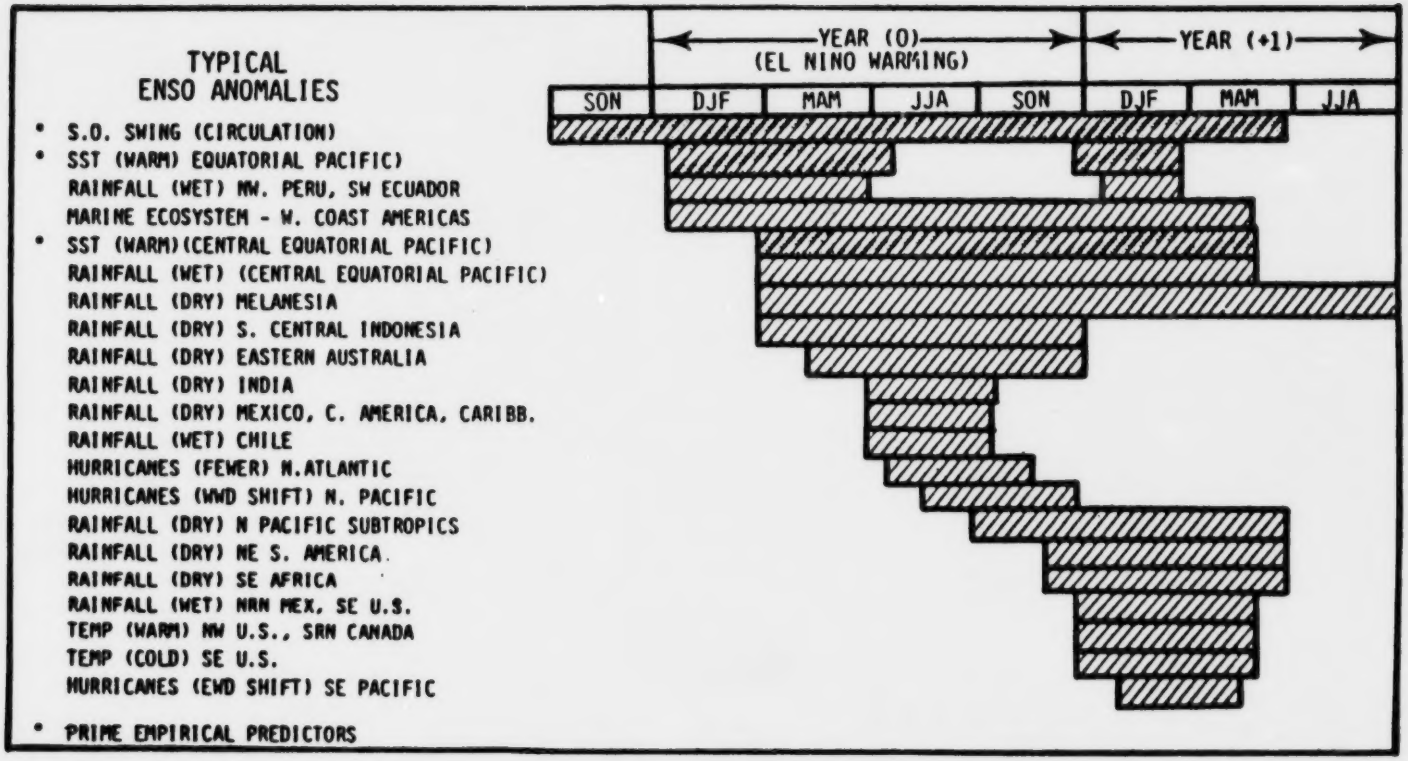


Figure 6. Chronology of major anomalies during a typical ENSO episode (Rasmusson, 1986).

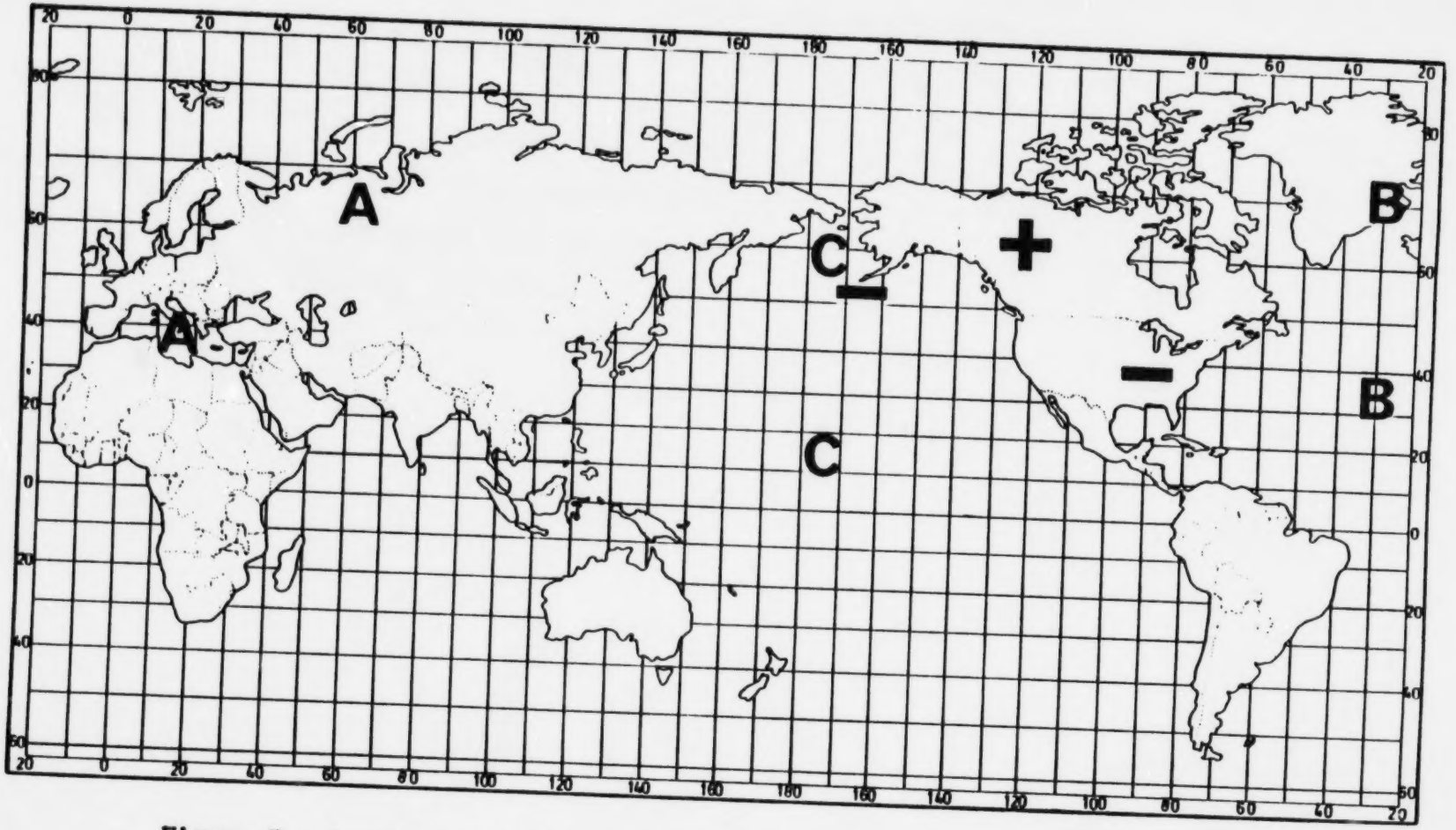


Figure 7 - Locations of major persistent atmospheric circulation anomalies (A - Northern Oscillation; B - North Atlantic Oscillation; C - North Pacific Oscillation; + and - indicate the positions and signs of the sea-level pressure anomalies associated with the Pacific North America anomaly).

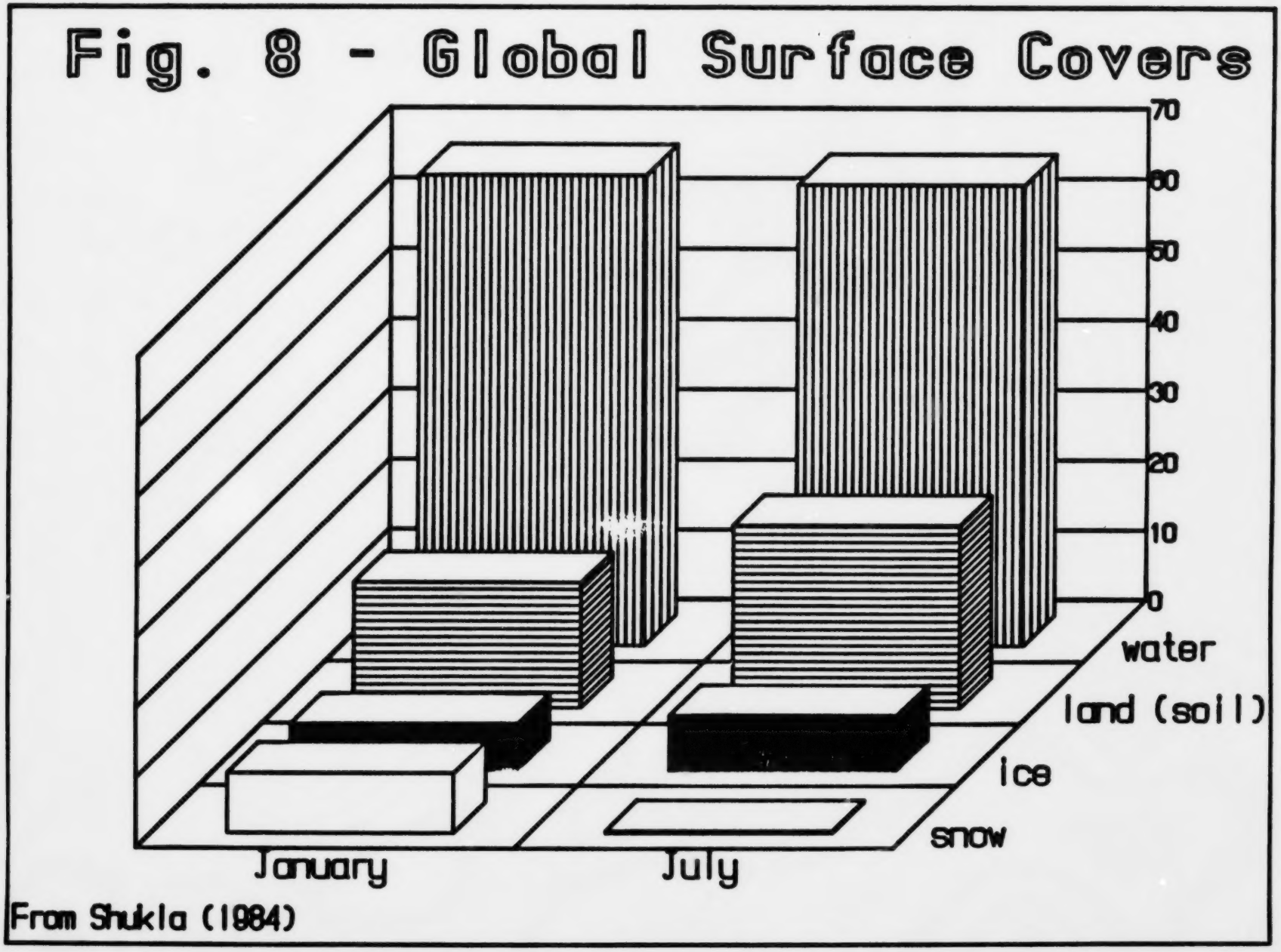


Fig. 8 - Global Surface Covers
70
60
50
40
30
20
10
0
water
land (soil)
ice
snow
January
July
From Shukla (1984)

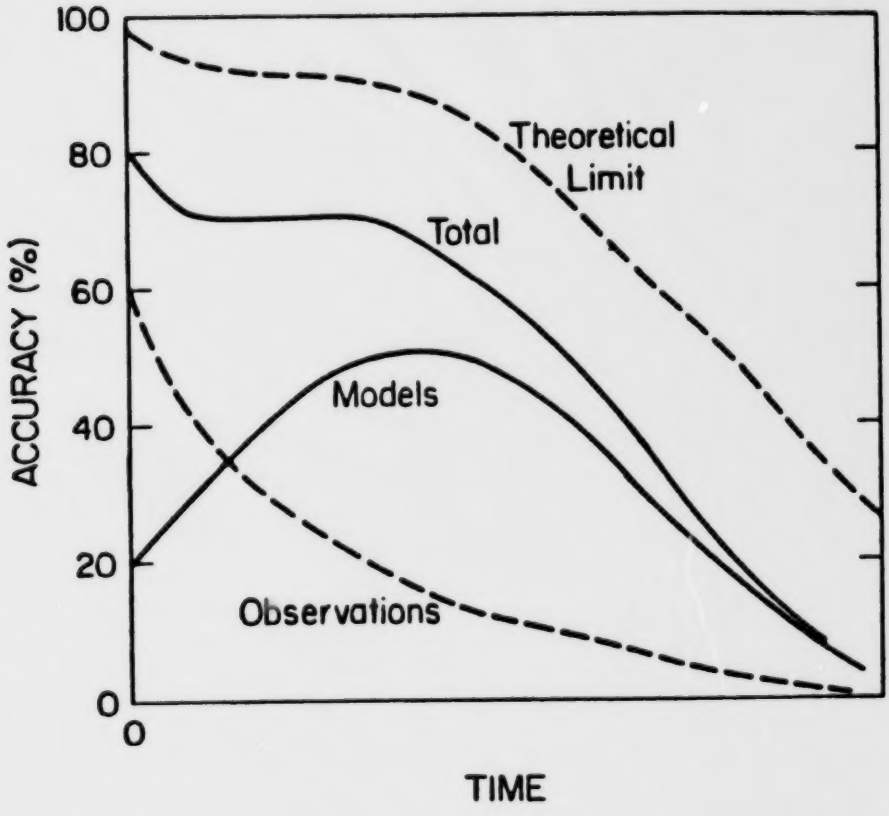
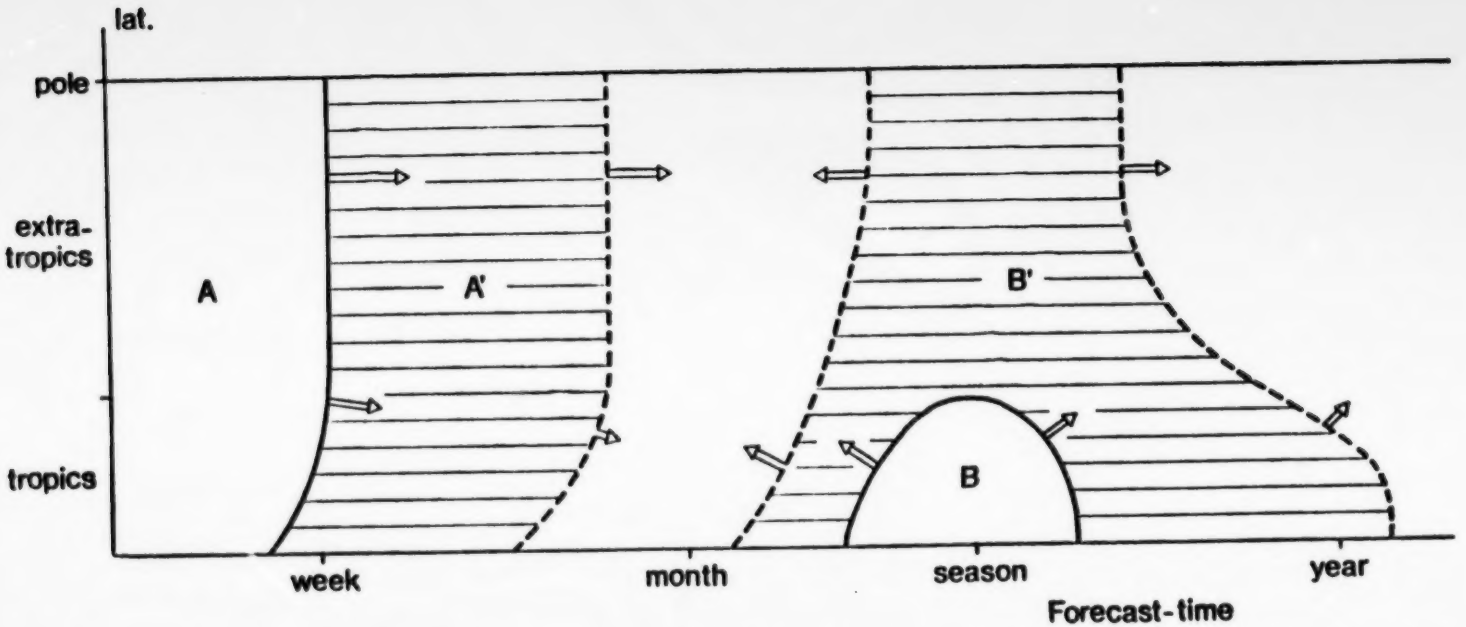


Figure 9. Relative contributions of observations and models to the predictability of atmospheric phenomena (Anthes and Baumhefner, 1984).



A schematic diagram with forecast time on a logarithmic scale along the horizontal axis and latitude along the vertical axis. The solid lines show present limitations for forecasts in an approximate way, while the dashed lines show the same at some future time. Arrows indicate the directions of improvements. The various areas signify the models which may be characterized as follows:

A : Forecasts performed using the most sophisticated available computer models of the atmosphere.

A': The possible future expansion of A.

B : Forecasts with a high statistical content, performed using a combination of statistical techniques and a variety of models representing the atmosphere and the coupled atmosphere-ocean system.

B': The possible future expansion of B.

Figure 10. Present and future capabilities of forecast methodologies (Anonymous, 1987).

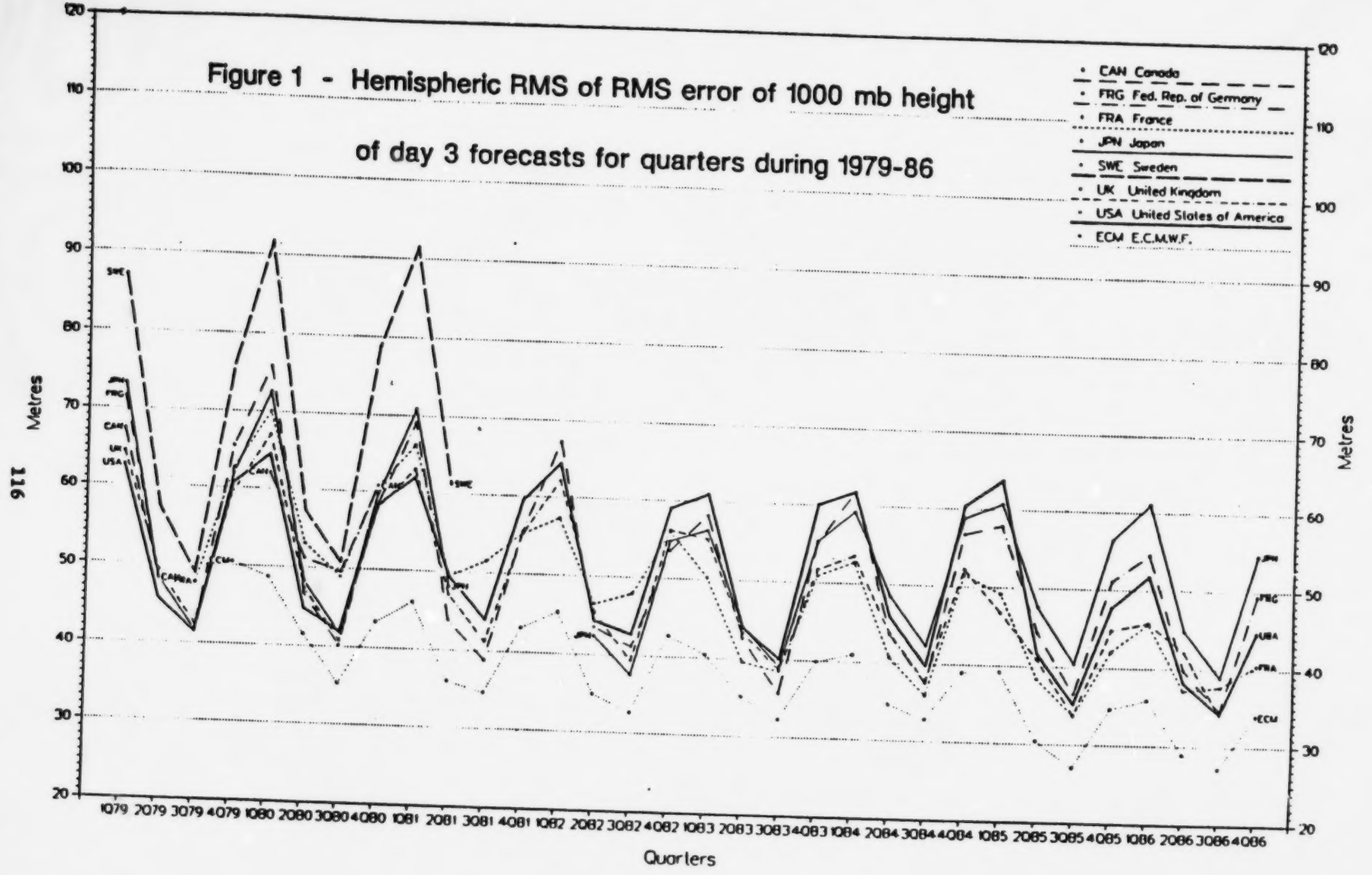


Figure 1 - Hemispheric RMS of RMS error of 1000 mb height
of day 3 forecasts for quarters during 1979-86
CAN Canada
FRG Fed. Rep. of Germany
FRA France
JPN Japan
SWE Sweden
UK United Kingdom
USA United States of America
ECM E.C.M.W.F.
Metres
Quarters
1079 2079 3079 4079 1080 2080 3080 4080 1081 2081 3081 4081 1082 2082 3082 4082 1083 2083 3083 4083 1084 2084 3084 4084 1085 2085 3085 4085 1086 2086 3086 4086

Figure 11. Comparison of skill of numerical forecast from a number of countries during the 1979-86 period (from European Centre for Medium Range Weather Forecasts).

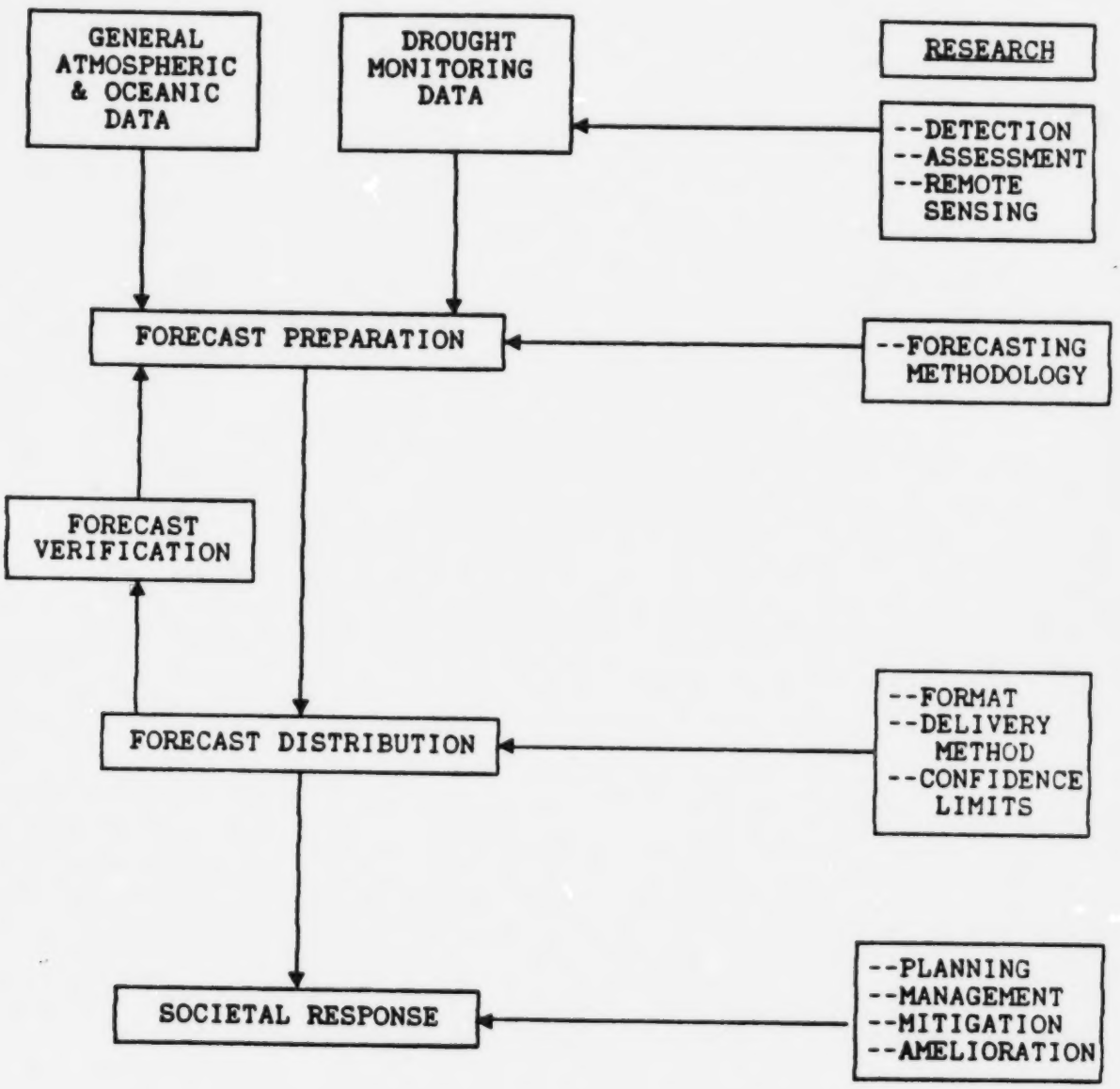


Figure 12 -- The drought forecast system.

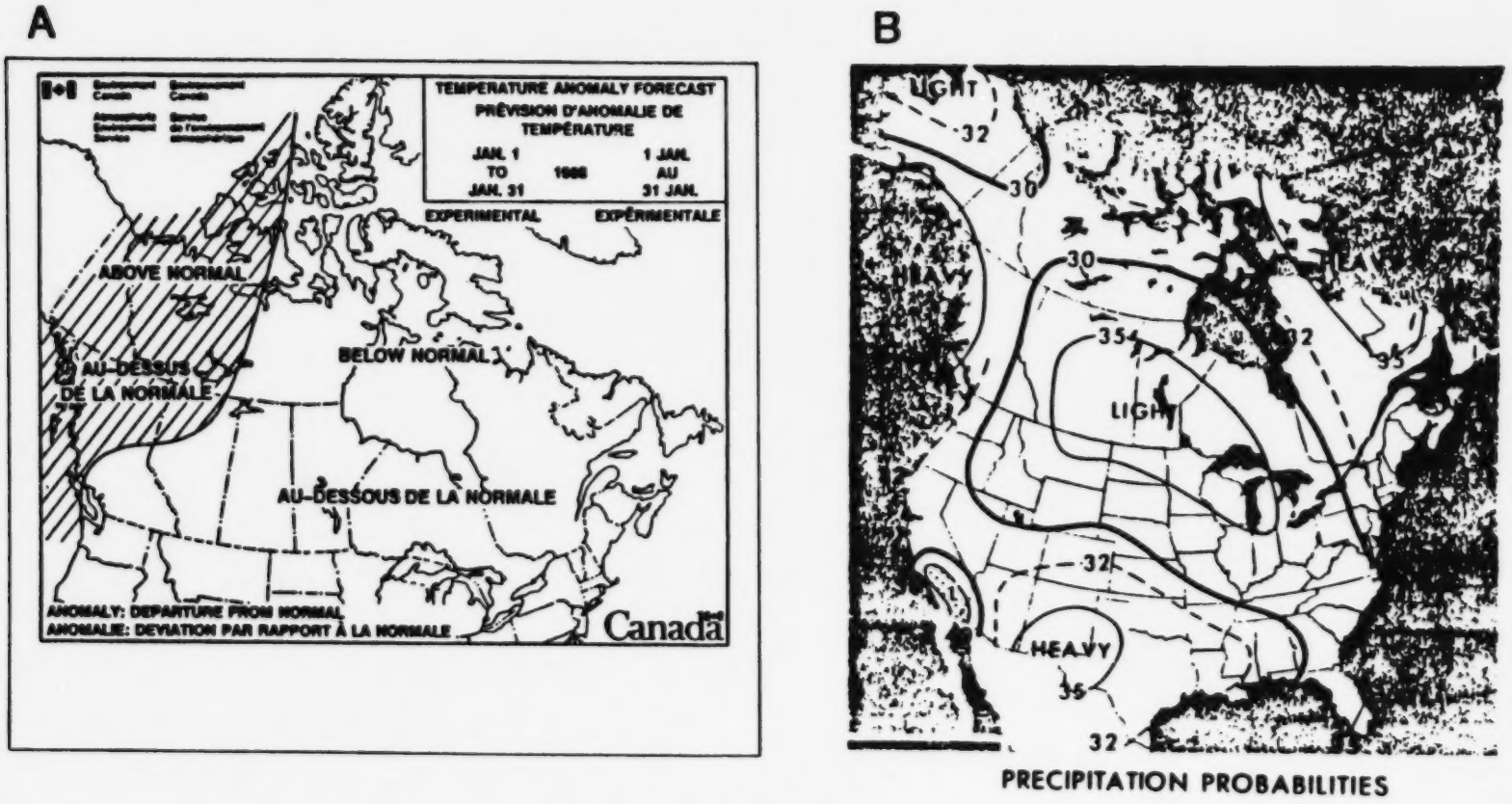


Figure 13. Short-term climate prediction formats as used by the:
A. Canadian Climate Centre, and
B. U.S. Climate Analysis Center.

FORECAST FOR THE PERIOD COMMENCING JUNE 1st ENDING JUNE 30th 1987

PART 1 BEST ESTIMATE FORECASTS:

TEMPERATURE (DEGREES C) AS A DIFFERENCE FROM NORMAL AND RAINFALL AS A PERCENTAGE OF NORMAL FOR EACH DISTRICT

(1) FIRST 15 DAYS

DISTRICT	0	1	2	3	4	5	6	7	8	9
TEMP.	0.2	0.5	0.5	0.7	0.5	0.2	0.0	0.0	0.0	0.5
RAINFALL	145	140	110	100	120	100	180	135	120	145

CONFIDENCE: C

(2) REMAINDER OF PERIOD

DISTRICT	0	1	2	3	4	5	6	7	8	9
TEMP.	-0.5	-1.0	-0.5	-0.5	-0.5	-1.0	-0.5	-0.5	-0.5	-0.5
RAINFALL	120	160	160	160	180	180	160	200	200	200

CONFIDENCE: C

PART 2 PROBABILITY FORECASTS FOR THE WHOLE PERIOD, (TEMP. AND RAINFALL)

TEMPERATURE PERCENTAGE PROBABILITY:

	MUCH BELOW AVERAGE	BELOW AVERAGE	AVERAGE	ABOVE AVERAGE	MUCH ABOVE AVERAGE
DISTRICTS: 0,6,7	5	25	50	15	5
1,5,8	15	50	20	10	5
2,9	5	20	50	20	5
3,4	5	15	50	25	5

RAINFALL PERCENTAGE PROBABILITY:

	BELOW AVERAGE	AVERAGE	ABOVE AVERAGE
DISTRICTS: 0,1,2,3,4,5,6,7,8,9	15	25	60

STRONG WIND EXPECTATION:

Above normal

DESCRIPTION OF WEATHER EXPECTED DURING THE PERIOD.

The month as a whole is expected to be unsettled with some very wet spells at times. Temperatures will be mostly near average, though it will be generally rather cool in the second half of the month.

OVERALL CONFIDENCE: C

© CROWN COPYRIGHT

ORIGIN: MET O 13 BRACKNELL

EXT: 2695 TELEX 849801

DATE/TIME 1st JUNE 1987/1535

THIS FORECAST IS NOT TO BE QUOTED WITHOUT REFERENCE TO THE ORIGINATORS.

Figure 14. Short-term climate prediction format used by the United Kingdom Meteorological Office.

Appendix A

Forecast and Research Centres Visited -- Experts Consulted

2 October 1987
Canadian Climate Centre
4905 Dufferin Street
Downsview, ON M3H 5T4, Canada

(Roger Daley, Stewart Cohen, Roger Street, Bruce Findlay, Paul Louie, John Knox, Peter Lee, Peter Scholefield, Amir Shabbar, George Boer)

5 October 1987
National Meteorological Center
National Oceanic and Atmospheric Administration
Washington, DC 20233, U. S. A.

(Eugene Rasmusson, Robert Livezey)

6 October 1987
Department of Meteorology
University of Maryland
College Park, MD 20742, U. S. A.

(Jagadish Shukla)

Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, MD 20771, U. S. A.

(Robert Atlas, Noah Wolfson, Yanish Sud)

9 October 1987
Climatic Research Unit
University of East Anglia
Norwich NR4 7TJ, United Kingdom

(Graham Farmer, Clare Goddess, Richard Warrick)

12 October 1987
Meteorological Office
London Road
Bracknell, Berks. RG12 2SZ, United Kingdom

(David Jones, Alan Dickinson, David Parker, Chris Folland, John Owen)

13 October 1987
European Centre for Medium Range Weather Forecasts
Shinfield Park
Reading, Berks. RG2 9AX, United Kingdom

(Austin Woods, Tim Palmer)

Department of Meteorology
University of Reading
Reading, Berks. RG6 2AU, United Kingdom

(R.P. Pearce, Mike Pedder, James Morison, J.R. Milford)

15 October 1987
Institute of Hydrology
Maclean Building
Crowmarsh Gifford
Wallingford, Oxon. OX10 8BB, United Kingdom

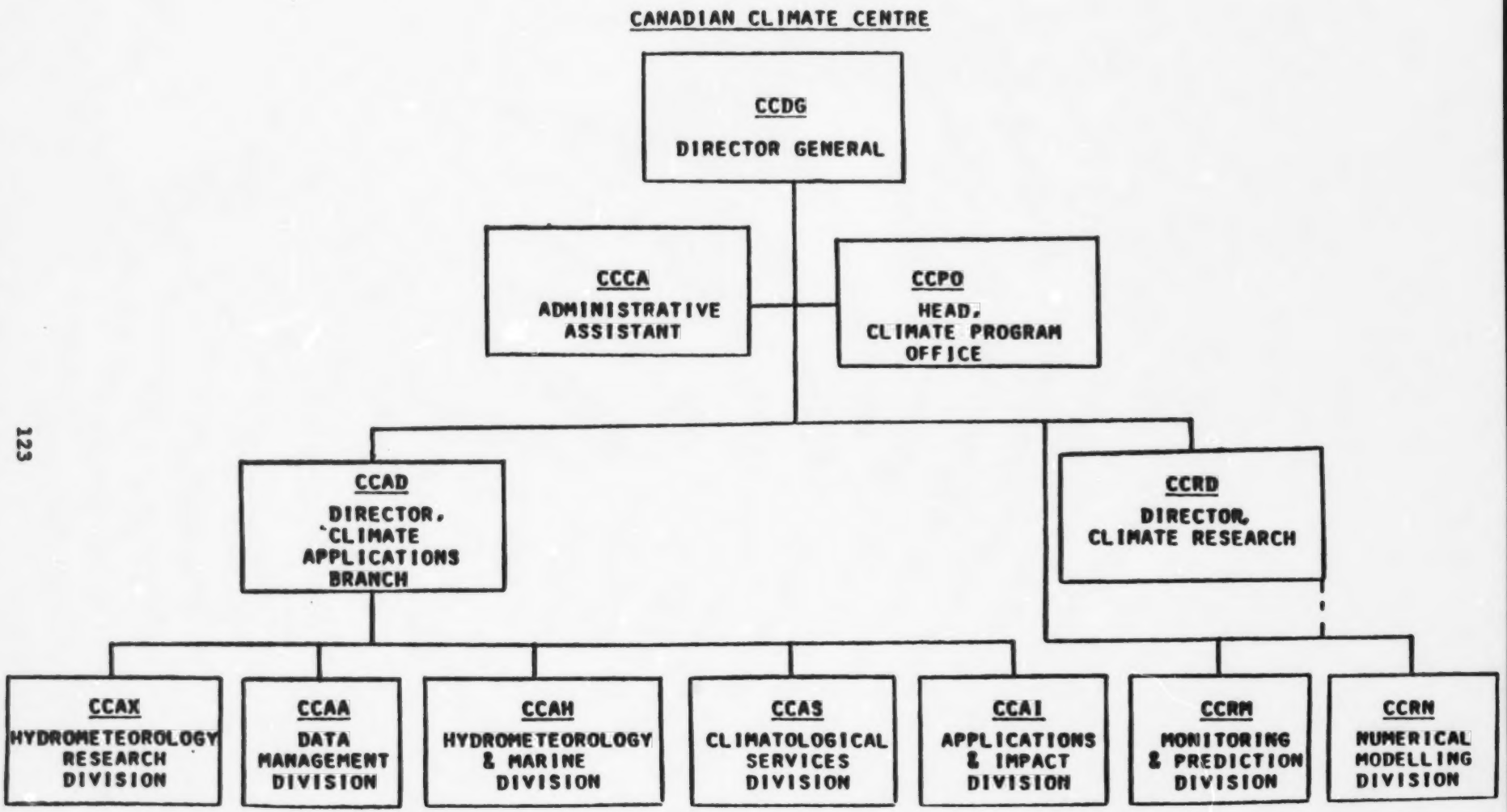
(Max Beran)

26 October 1987
Climate Research Group
Scripps Institution of Oceanography
La Jolla, CA 92093, U. S. A.

(Daniel Cayan, John Roads, Nick Graham)

27/28 October 1987
National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80307-3000, U. S. A.

(Phil. Merilees, Gerald Meehl, Akira Kasahara, Harry Van Loon, Joseph Tribbia, Michael Glantz, D. Baumhefner, Robert Dickinson, Roy Jenne)


CANADIAN CLIMATE CENTRE
CCDG
DIRECTOR GENERAL
CCCA
ADMINISTRATIVE ASSISTANT
CCPO
HEAD, CLIMATE PROGRAM OFFICE
CCAD
DIRECTOR, CLIMATE APPLICATIONS BRANCH
CCRD
DIRECTOR, CLIMATE RESEARCH
CCAX
HYDROMETEOROLOGY RESEARCH DIVISION
CCAA
DATA MANAGEMENT DIVISION
CCAH
HYDROMETEOROLOGY & MARINE DIVISION
CCAS
CLIMATOLOGICAL SERVICES DIVISION
CCAI
APPLICATIONS & IMPACT DIVISION
CCRM
MONITORING & PREDICTION DIVISION
CCRN
NUMERICAL MODELLING DIVISION

NMC/CLIMATE ANALYSIS CENTER

Chief, D.R. Rodenhuis

OFFICE OF THE CHIEF

E.S. Epstein
R.L. Lehman
G.S. Lucas
L.P. Mannello

PREDICTION BRANCH
Chief, D.L. Gilman

A.G. Barnston
W. -Y. Chen
R.D. Dickson
D.B. Durdall
M.C. Gaidurgis
R.E. Livezey[1]
T.N. Maisel
R.E. Taubensee
M.S. Tracton
D.L. Vanderbrink
A.J. Wagner

DIAGNOSTICS BRANCH
Chief, E.M. Rasmusson

P.A. Arkin
M.S. Halpert
J.E. Janowiak
J.D. Kopman
V.E. Kousky
E.A. O'Lenic[2]
R.S. Quiroz[3]
R.W. Reynolds
C.F. Ropelewski
S.W. Saunders
A.D. Siegel
K.M. Stevenson

ANALYSIS & INFORMATION BRANCH
Chief, F.G. Finger

K.H. Bergman
V. Bjerknes
R.H. Churchill
J.M. Dionne
J.A. Fleming
G.G. Fulwood
M.E. Gelman
T.R. Heddinghaus
K. W. Johnson
M. Knezevic
J.D. Laver
M.R. McCalla
A.J. Miller
D. Miskus
R.M. Nagatani
V.L. Patterson
S.M. Piatt
P. Sabol
A.R. Thomas

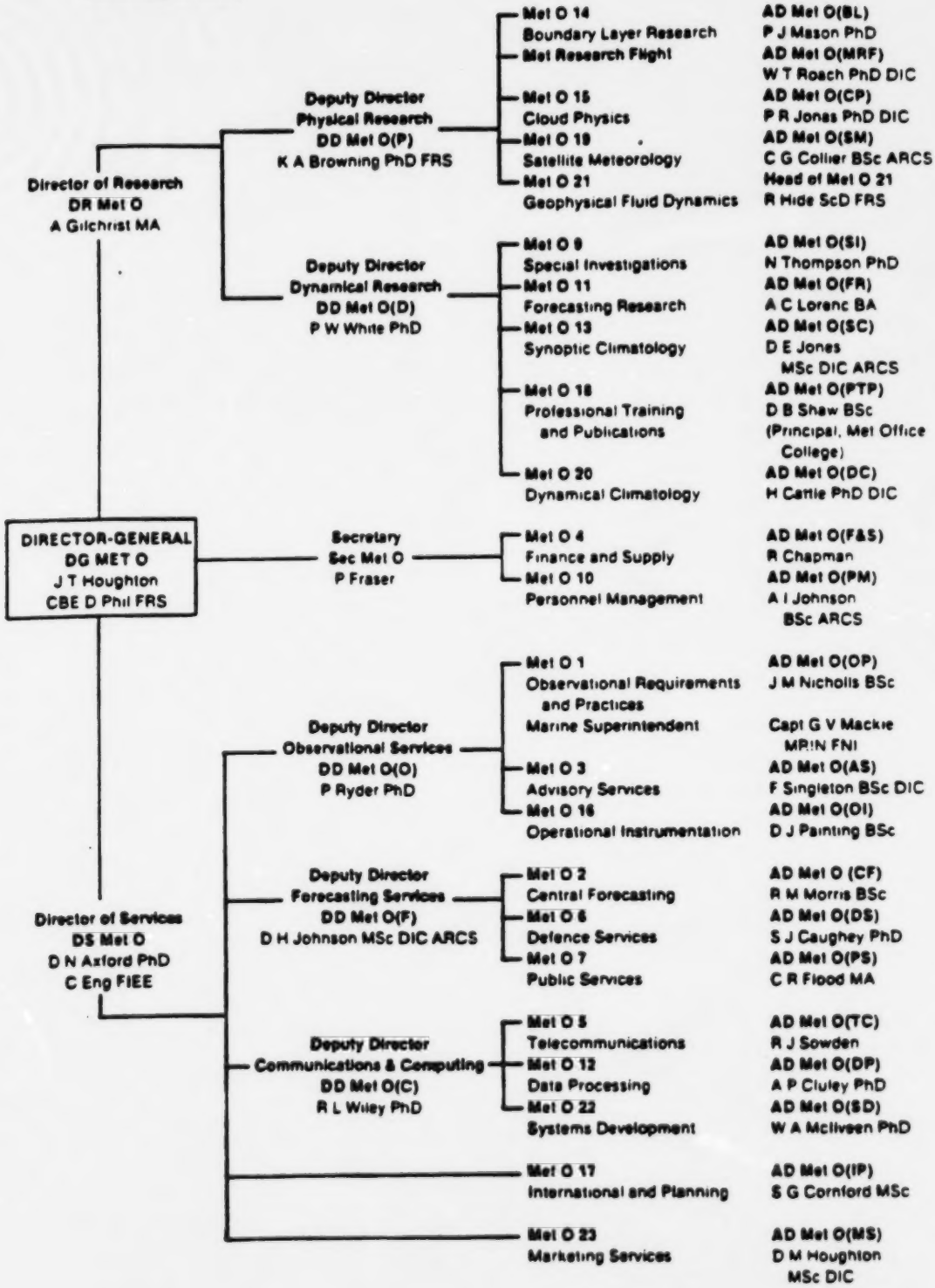
AGRICULTURAL WEATHER SECTION

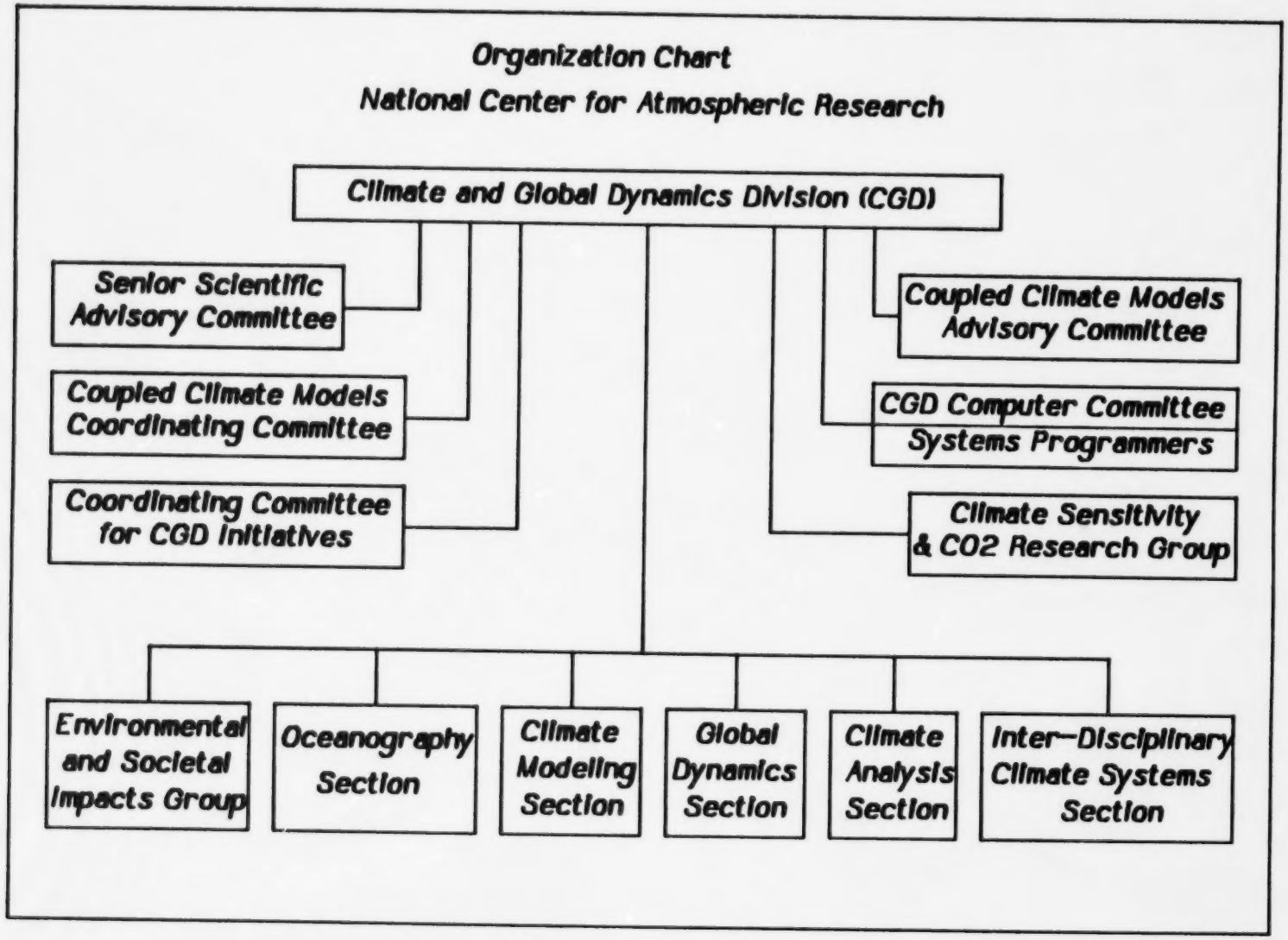
O.W. Byrd
C.A. Caleco
L.M. Denny
D.J. Haddock[4]
R.M. McInturff
J.T. Williams

[1] Transferred to NASA, Mar. 1985
[2] Attending U/Washington, Sept. 1985
[3] Retired, Sept. 1985
[4] Retired, Aug. 1985.

METEOROLOGICAL OFFICE HEADQUARTERS ORGANIZATION

(as at August 1987)




Organization Chart
National Center for Atmospheric Research
Climate and Global Dynamics Division (CGD)
Senior Scientific Advisory Committee
Coupled Climate Models Coordinating Committee
Coordinating Committee for CGD Initiatives
Coupled Climate Models Advisory Committee
CGD Computer Committee
Systems Programmers
Climate Sensitivity & CO2 Research Group
Environmental and Societal Impacts Group
Oceanography Section
Climate Modeling Section
Global Dynamics Section
Climate Analysis Section
Inter-Disciplinary Climate Systems Section

Appendix B

Drought Study -- User Questionnaire.

Preamble

It may be possible within the next decade or so to produce forecasts of drought conditions on the Prairies. Possible forecast periods may vary from a few weeks up to a year or more in advance.

The Hydrometeorological Research Division of the Canadian Climate Centre has commissioned us to carry out a survey of the needs of potential users of such forecasts.

We would be very grateful if you would agree to participate in this survey.

Questions

If such a forecast became a reality:

1. Would it be of interest to your organization?

2. What time frame (forecast period) would be most useful to you?

3. What geographical areas would you like it to cover?

4. What use would you make of the forecast?

5. What type of forecast would you prefer?

general.....specific

TIME SCALE

SPACE SCALE

DROUGHT SEVERITY SCALE

6. How would you like the drought severity to be expressed?

7. What weather elements would you like to have included?

none specifically;
precipitation (amount, intensity, seasonal timing);
evapotranspiration;
wind;
sunshine;
temperature;
others such as drought indices, etc.

8. Would you like the forecast to be expressed in terms of probability?

9. Would you also be interested in forecasts of wet periods?

10. How often would you need such forecasts, and at what times of the year?

11. What value would such forecasts have to you?

12. Comments?

List of Potential Users Interviewed.

AES Scientific Services, Regina, SK (Ken Jones)

Agriculture Canada Research Station, Melfort, SK
(Stan Beacom)
Agriculture Canada Research Station, Swift Current, SK
(Herb. Cutforth)
Agriculture Canada Research Station, Swift Current, SK
(Howard Harding)

Alberta Agriculture, Irrigation & Conservation, Edmonton, AB
(David Neilson)

Canadian Forestry Service, Prince Albert, SK (Keith Gorham)

Canadian Wheat Board, Winnipeg, MB (Graham Walker)

Ducks Unlimited, Regina, SK (Dick Iverson)

Environment Canada, Inland Waters, Regina, SK (Jim Rogers)

Environment Canada, Water Resources Branch, Regina, SK
(Ross Herrington)

Manitoba Hydro, Winnipeg, MB (Peter Abel)

Prairie Farm Rehabilitation Administration, Regina, SK
(Ted O'Brien)
Prairie Farm Rehabilitation Administration, Winnipeg, MB
(Erminio Caligiuri)
Prairie Farm Rehabilitation Administration, Calgary, AB
(Walter Nemanishen)
Prairie Farm Rehabilitation Administration, Hanna, AB
(P.H. Larson)

Prairie Provincial Water Board, Regina, SK (Richard Kellow)

Saskatchewan Agriculture, Regina, SK
(Doug England, John Buchan, Ken Peterson, Blair Harris)
Saskatchewan Agriculture, Shellbrook, SK
(Harold Amundson)

Saskatchewan Crop Insurance Corporation, Melville, SK

Saskatchewan Parks & Renewable Resources, Regina, SK
(Wayne Pepper)

Saskatchewan Research Council, Saskatoon, SK
(John Maybank, Elaine Wheaton)

South Saskatchewan River Basin Study, Regina, SK
(Stephen Kendall)

University of Saskatchewan, Division of Hydrology, Saskatoon, SK
(Don Gray)

Summary of User Survey

1. All those who responded, with only one exception, were interested in the hypothetical drought forecast.

2. Desired forecast periods varied from a week to several years. However, most respondents were interested in the month to season range.

3. This varied considerably with the respondent's area of interest, ranging from the agricultural areas of the Prairies to the forested areas and all of the watersheds. Those with hydrological interests wished for a breakdown by drainage basin, while agriculturalists and ecologists wished for a crop district, or vegetation or soil zone breakdown.

4. The main potential uses of the forecast were:
   planning - for drought mitigation;
   advisory - to inform constituents of impending water availability and soil moisture conditions;
   budgetting - to deal with potential drought-related expenses, such as forest fire control;
   policy - decisions on future water-related projects;
   education and research;
   computer modelling.

5. While a few respondents would be satisfied with a general type of forecast, most would prefer one specific to their particular interests.

6. Most would prefer precipitation expressed as percent of normal. Some want drought or crop moisture indices, other would like an estimate of potential effects on crops or water supplies. Some respondents suggested that drought timing and its effect on water availability would be important.

7. While precipitation and temperature were the most desired elements, some respondents were interested in evapotranspiration, wind and sunshine as well.

8. Most were in favour of the use of probability, but some pointed out that degree of confidence would be more important.

9. Nearly all respondent were also interested in forecasts of wet periods as well, specifically in terms of precipitation amounts, duration and frequency of occurrence.

10. The majority would prefer a monthly issuing frequency, although some require it only seasonally or twice a year. A few would like more frequent updates.

11. There was general agreement that the forecast, if accurate, would be of great value.

12. Some users would like a detailed explanation to accompany the forecast, explaining on what factors it was being based, be they sea-surface temperatures or sunspot numbers. Others believe that assessment of forecast accuracy, and its communication to users, is very important in order to establish its credibility. Still others would like to become involved in the evolution of the forecast methodology.

Appendix C

Data Inputs

Sources of data

Most national weather services provide catalogues of their own meteorological data as, for example, Phillips (1982) for Canada and Hatch (1986) for the U.S.A. For the world as a whole, catalogues may be found in some World Meteorlogical Organization publications (World Meteorological Organization, 1969-75; World Meteorological Programme, 1985) and a very comprehensive survey of meteorological databases has been published by Jenne and McKee (1985). Major data banks are located at the National Climatic Data Center in Asheville, NC, the National Center for Atmospheric Research in Boulder, CO, and the World Data Center A, University of Colorado, Boulder, CO.

Requirements for current data can be met through the use of real-time (or near real-time) data communication systems. Historical databases may be stored at the forecast site, or accessed from a data bank through a communications link. It is likely that within a few years time high-capacity storage devices, such as compact disks, will permit the on-site storage of all but the largest databases.

Historical data for drought-forecasting research purposes will likely form a superset of those required for actual forecasting. Some historical datasets are in the form of actual point observations, from surface or upper-air observing stations, while others have been gridded, a usually much more useful form for climate diagnostic studies. Data may come from manual or automated surface observing stations, from balloon or rocket-borne upper air sensors, or from satellite or other type of remote sensing, and may be observed on a routine, or once-only basis.

Dataset preparation

Most observed data suffer from some errors and inaccuracies, and require a considerable amount of checking and correction before they become useful for climate studies and forecast operations (Jenne and Joseph, 1978; KelResearch Corp., 1985; Wright, 1986b). Changes in instrumentation, time and place of observation, automation, etc. introduce systematic errors into data sets, particularly those that span long periods of time. Accordingly, a lot of effort has been put into "cleaning up" these data by a number of research groups, such as those at the National Center for Atmospheric Research (Jenne, 1975) and the University of East Anglia's Climate Research Unit (Bradley et al, 1985), for example.

A good example of the processing of a large volume of point observations into an edited gridded database is the Comprehensive Ocean-Atmosphere Data Set (COADS). The original data consisted of over 70 million unique reports containing 28 parameters, observed by ocean-going vessels over the period of 1854-1979. These data have been collected, edited and summarized statistically for each month of each year, using a 2° latitude by 2° longitude grid (Slutz et al, 1985). The data are now available on magnetic tapes from NCAR, Boulder.

Basic input data

Weather conditions for the very near future are controlled mainly by local conditions at the present time, i.e. by the initial conditions. As the period of interest is extended into the future, atmospheric motions become important as do more remote surface boundary conditions (Hoskins and Sardeshmukh, 1987). Thus, the preparation of a 12-36 hour forecast of the 50 kPa flow at a latitude of 40° N requires input data only between the 250 and 700 kPa levels, and between latitudes 20 and 70° N, while a forecast for a 1 week to 2 month period requires information describing the state not only of the entire global atmosphere, but of the top 100 m of global ocean as well.

The data information requirements for climate diagnostic studies and forecasting are classified below, followed by a number of references relevant to drought forecasting.

Comprehensive datasets

These include a large number of parameters, usually coming from a variety of sources.

Bradley et al (1985)
Jenne (1975)
Slutz et al (1985)
Trenberth and Paolino (1980)
Woodruff et al (1987)

Gridded datasets

These data have been collated and summarized statistically into average values for latitude-longitude boxes of various sizes.

Jones et al (1986)
Matthews (1983)
Slutz et al (1985)
Trenberth and Paolino (1980)
Woodruff et al (1987)

Surface atmospheric data

These data include the standard climatological station parameters: temperature, humidity, wind, pressure, etc.

Cayan et al (1986)
Namias (1975)
Newell et al (1982)
Robock (1982)
Ropelewski and Jones (1987)

Upper-air atmospheric data

These data include the standard upper-level atmospheric parameters: temperature, humidity, wind, pressure, etc.

Dunn (1983; 1984)
Namias (1979; 1981a)

Land-surface data

These include data describing land-surface conditions, such as topography, surface temperature, surface albedo, snow and ice cover, vegetation cover and land use, surface water cover, soil moisture, etc.

Barry and Shartran (1979)
Berkofsky and Bertoni (1955)
Bradley et al (1987)
Henderson-Sellers and Wilson (1983)
Henderson-Sellers et al (1986)
Matson et al (1986)
Matson and Wiesnet (1981)
Matthews (1983)
McGinnis and Tarpley (1985)
Ropelewski (1983; 1985)
Scialdone and Robock (1987)
Tucker et al (1985)
Wilson and Henderson-Sellers (1985)

Oceanic data

These include sea-surface temperatures, sea level, salinity, ocean depths and currents, sea ice cover, etc.

Barry and Shartran (1979)
Cavalieri and Zwally (1985)
Cayan (1986)
Folland et al (1984)
Harries et al (1983)
Kelly (1979)
Markham (1980; 1981)
Woods (1983)

Satellite data

This category includes all data collected by remote sensing, mainly from satellites.

Atlas et al (1985)
Cavalieri and Zwally (1985)
Isaacs et al (1986)
Matson and Wiesnet (1981)
Matson et al (1986)
Matthews (1983)
McGinnis and Tarpley (1985)
Ropelewski (1985)
Schiffer and Rossow (1985)
Woods (1983)

Maps, atlasses and charts

Included under this category are mapped observational data, often averaged over a period of time such as a month or a season, charts of deviations from average (anomalies), and spatial correlation (teleconnection) charts.

Arkin et al (1983; 1986)
Augulis (1969)
Cayan (1986)
Cayan et al (1986)
Dunn (1983; 1984)
Markham (1980; 1981)
Matson et al (1986)
Namias (1975; 1979; 1981a)
Newell et al (1982)
Rasch and MacDonald (1975)
Wagner and Maisel (1987)

Data processing, analysis and display

This includes information on the handling, preliminary analysis and presentation of meteorological data. An example is the WMO CLICOM microcomputer package.

Folland and Bottomley (1986)
Grotch (1987)
Jenne and Joseph (1978)
KelResearch Corp.(1985)
Lewis (1987)
Mobley and Preisendorfer (1985)
Reynolds et al (1987)
Ropelewski et al (1985)
World Climate Data Programme (1986)
Wright (1986b)

Data catalogues

Catalogues of data available from national meteorological services, the World Meteorological Organization, and national and international data repositories are included here.

Finger et al (1985), The Climate Analysis Center's User Information Service, Bull.Amer.Met.Soc.66:413-420

Hatch (1986), Selective Guide to Climatic Sources, National Climate Center, NOAA, Asheville, NC

Jenne and McKee (1985), Data, pp.1175-1281 in: D.D. Houghton (Ed.), Handbook of Applied Meteorology, John Wiley, New York

Phillips (1982), Handbook on Climate Data Sources of the Atmospheric Environment Service, Canadian Climate Centre, Downsview, ON

World Meteorological Organization (1965-79), Catalogue of Meteorological Data For Research (in four parts), WMO No.174, Geneva

World Meteorological Organization (1985), Infoclima Catalogue of Climate System Data Sets, WCP-101, WMO, Geneva

Climate bulletins

Many national meteorological services issue weather and climate bulletins at weekly, monthly, or other intervals. These usually include summaries of past and present conditions, often together with weather forecasts and climate outlooks. These will be discussed more fully in the section on forecast delivery.

Canadian Climate Centre, Climatic Perspectives, Atmospheric Environment Service, Downsview, ON

Climate Analysis Center, Climate Diagnostics Bulletin, National Weather Service, NOAA, Washington, DC

Climate Analysis Center, Monthly and Seasonal Weather Outlook, National Weather Service, NOAA, Washington, DC

Japan Meteorological Agency, Monthly Report on Climate System.

Long-Range Forecast Division, Forecast Department., 1-3-4, Otc-machi, Chiyoda-ku, Tokyo, Japan

Ross, T.G. (Ed.), National Water Conditions, US Dept. of the Interior, Geological Branch, and Canada Dept. of the Environment, Water Res. Branch

World Climate Data Programme, Climate System Monitoring Monthly Bulletin, W.M.O., Geneva, Switzerland

Major reports

This includes recent conference reports relating to drought and long-range forecasting.

Beran, M.A. and J.A. Rodier (1985), Hydrological Aspects of Drought, UNESCO/WMO, Paris and Geneva, 149 pp.

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